Nucleon Physics at Large x

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Lecture I

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Outline

- *Introduction*
- *Deep inelastic lepton scattering*
- *Nucleon structure in the Valence quark region*
- *Moment of structure functions and sum rules*
  - *Gerasimov-Drell-Hearn and Bjorken Sum Rules*
- *Quark Gluon correlations Polarizabilities; Spin and color*
- *Semi-Inclusive scattering and Transverse momentum distributions*

Introduction

- *A physics goal in our field (of strong interaction) is to understand the structure of hadrons.*
- *The theory for doing that is well established in its perturbative regime (when the running coupling constant is small) and is called Quantum ChromoDynamics (QCD)*
- *However, this theory is difficult to solve when the coupling constant is large, a regime known as the confinement regime*
- *Experiments to investigate the structure of hadrons have helped in the past to test the theory in its perturbative regime and provide for challenges in the confinement regime.*

Studying the structure of hadrons

How?

⇨ *Rutherford tradition of scattering experiments*

⇨ *Using a super high resolution transmission electron (lepton) microscopes*

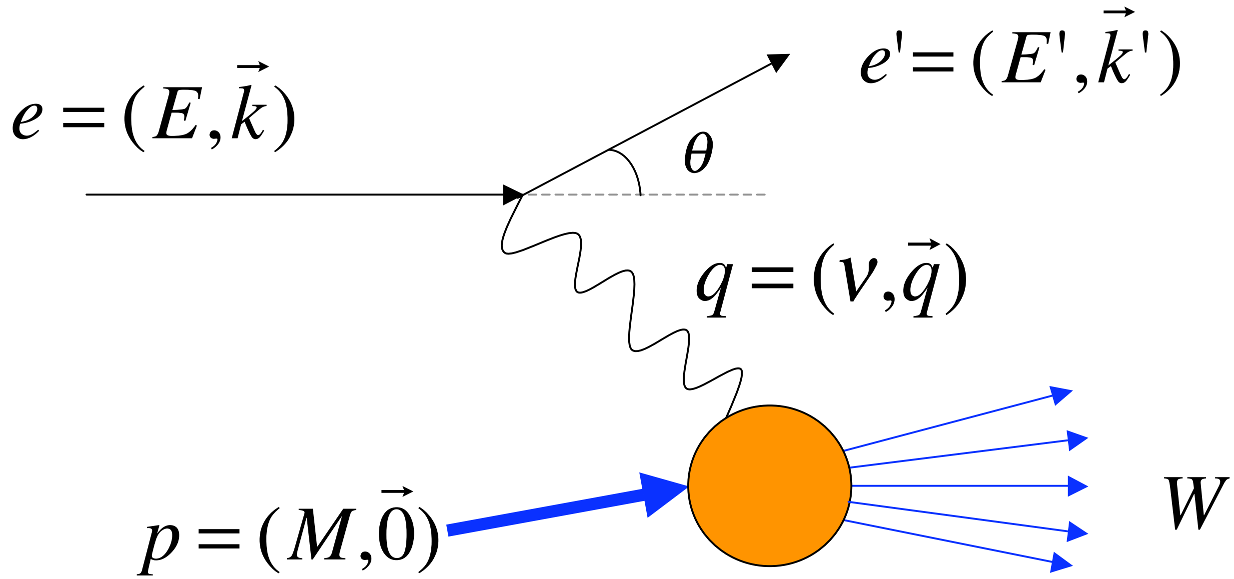
SLAC

CERN

DESY

Jefferson Lab

Lepton Scattering



- *4-momentum transfer squared:* $Q^2 = -q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right)$
- *Invariant mass squared:* $W^2 = M^2 + 2M\nu - Q^2$
- *Bjorken variable:* $x = \frac{Q^2}{2M\nu}$

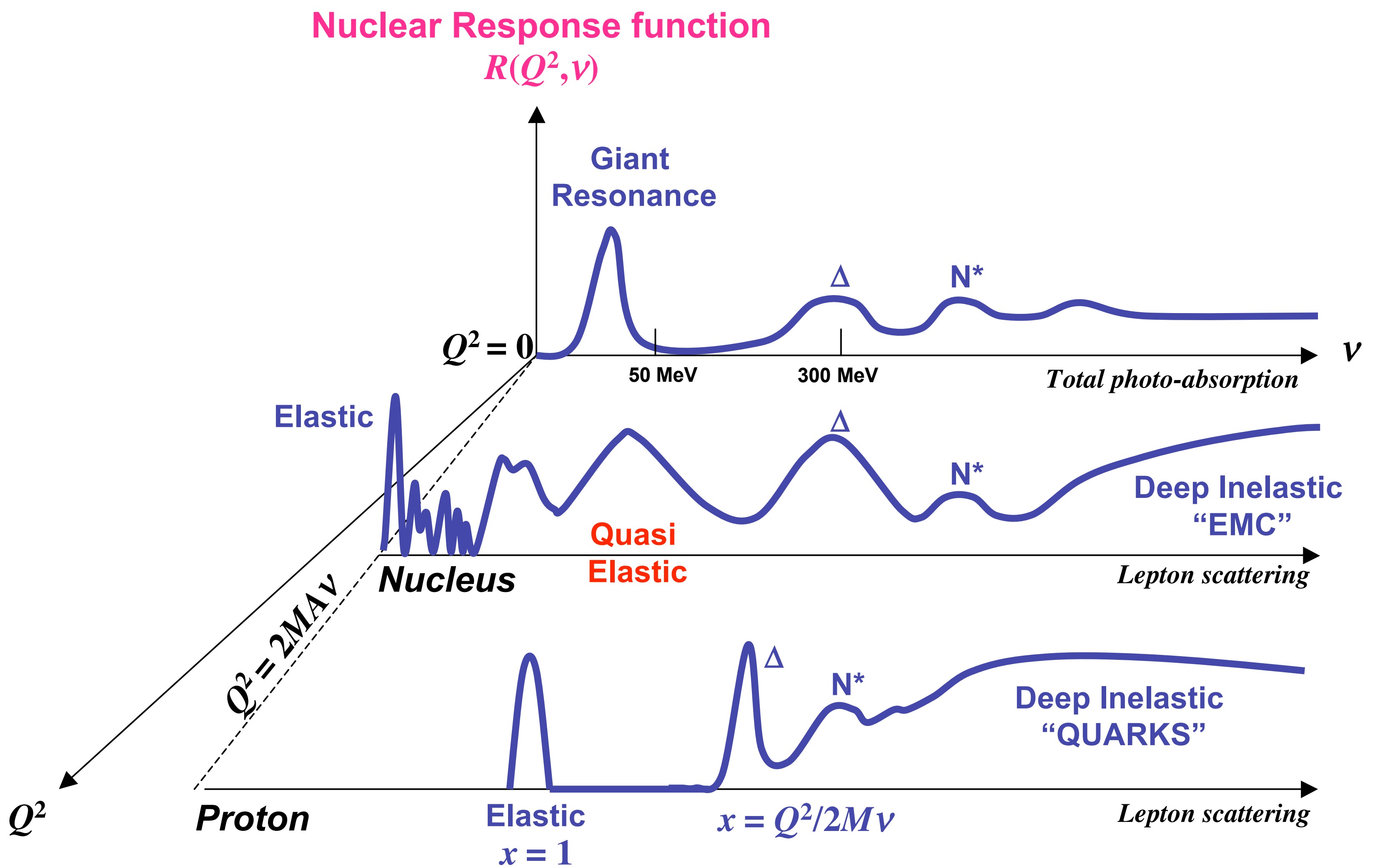
Quantum Electrodynamics

Feynman diagrams ⇒ Matrix element ⇒ Fermi's Golden Rule ⇒ Transition probability ⇒ Cross section

Example of inclusive electron scattering

$$\boxed{\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}}$$

Nucleus/nucleon response to electromagnetic scattering

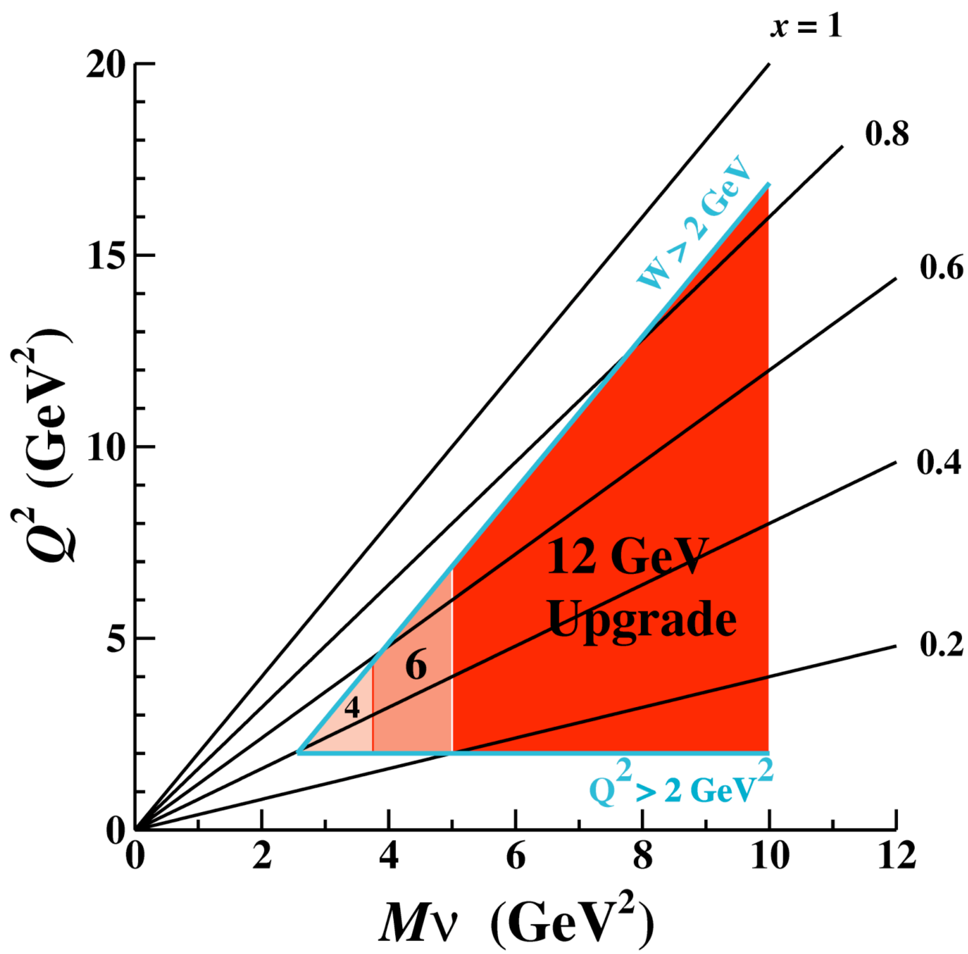


Kinematics Variables and Invariants

Variable	Description	Value in Lab Frame
s	*Incident lepton spin four-vector*	$\frac{1}{m}(\lvert\vec{k}\rvert, 0, 0, E)$
S	*Target nucleon spin four-vector*	$(0, \vec{S})$
k	*Incident lepton four-momentum*	$(E, \vec{k})$
k'	*Scattered lepton four-momentum*	$(E', \vec{k}')$
P	*Target nucleon four-momentum*	$(M, \vec{0})$
q	*Virtual photon four-momentum transfer*	$q = k - k' = (\nu, \vec{q})$
θ	*Scattering angle of lepton*	
Invariants	**Description**	**Value in Lab Frame**
$Q^2 = -q^2$	*Four momentum transfer*	$\approx 4EE' \sin^2(\theta/2)$
ν	*Energy of virtual photon*	$P \cdot q/M = E - E'$
x	*Bjorken Scaling Variable*	$-q \cdot q/2P \cdot q = Q^2/2M\nu$
W^2	*Invariant mass of final hadronic state*	$(P + q)^2 = M^2 + 2M\nu - Q^2$

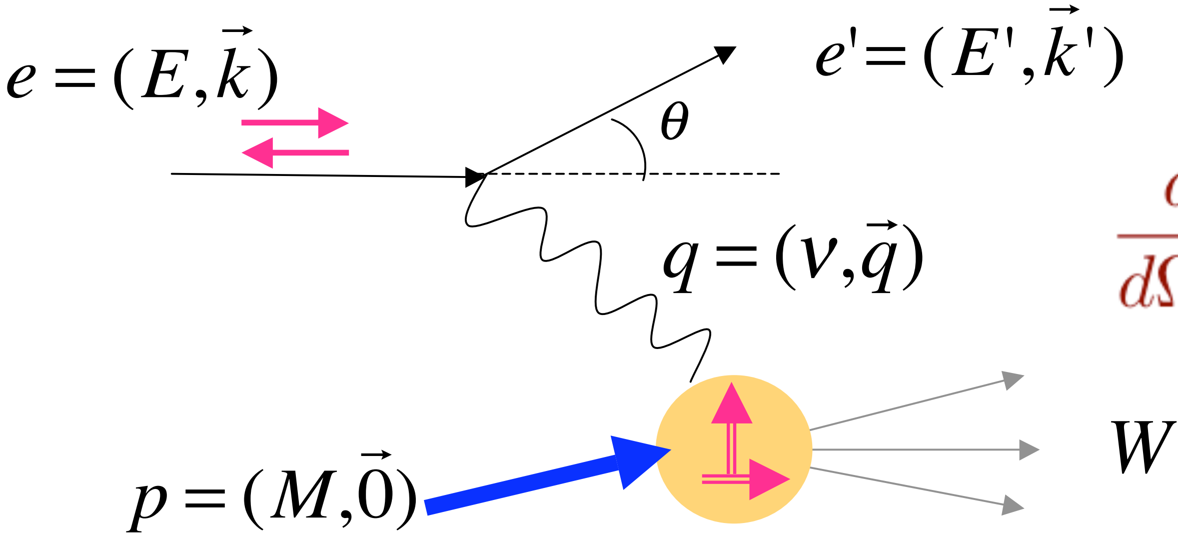
Example of Kinematical Reach; Jlab 12 GeV

- Access to very large x (x > 0.4)
  - Clean region
    - No strange sea effects
    - No explicit hard gluons to be included
- Quark models can be a powerful tool to investigate the structure of the nucleon
- Comparison with lattice QCD is possible for higher moments of structure functions.



Inclusive lepton scattering

The one photon exchange approximation



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

Leptonic tensor:

$$L_{\mu\nu} = L^S_{\mu\nu} + iL^A_{\mu\nu} = 2\left[k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu}\left(k\cdot k' - m^2\right) + im\epsilon_{\mu\nu\rho\sigma}q^\rho s^\sigma\right]$$

Hadronic Tensor:

$$W^{\mu\nu} = W^{\mu\nu}_S + iW^{\mu\nu}_A = \frac{1}{2\pi}\int d^4x\ e^{iq\cdot x} < P,S|[J_\mu(x),J_\nu(0)]|P,S >$$

Inclusive lepton scattering (continued)

- The *symmetric* part of the tensor is written in terms of two spin-independent structure functions $W_1(\nu,Q^2)$ and $W_2(\nu,Q^2)$:

$$W_S^{\mu\nu} = -\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) W_1 + \frac{1}{M^2}\left(P^\mu - \frac{P\cdot q}{q^2} q^\mu\right)\left((P^\nu - \frac{P\cdot q}{q^2} q^\nu\right) W_2$$

- The *antisymmetric* part of the tensor is similarely written in terms of two spin dependent structure functions $G_1(\nu,Q^2)$ and $G_2(\nu,Q^2)$

$$W_A^{\mu\nu} = WM\epsilon^{\mu\nu\rho\sigma} q_\rho s_\sigma G_1(\nu,Q^2) + \frac{1}{M}\epsilon^{\mu\nu\rho\sigma} q_\rho \left[(P\cdot q)S_\sigma - (S\cdot q)P_\sigma\right] G_2(\nu,Q^2)$$

- This decomposition is possible because the form of the tensor is constrained to be invariant under parity and time reversal. It must be hermitian: $W^{\mu\nu} = W^{\nu\mu *}$ and satisfy current conservation:

$$q_\mu W^{\mu\nu} = q_\nu W^{\mu\nu} = 0$$

Inclusive electron scattering cross sections

Unpolarized beam and target

$$\frac{1}{2}\left(\frac{d^2\sigma^{\downarrow\Uparrow}}{dE'd\Omega}+\frac{d^2\sigma^{\uparrow\Uparrow}}{dE'd\Omega}\right)=\frac{4\alpha^2}{Q^2}\left[2W_1(x,Q^2)\sin^2(\theta/2)+W_2(x,Q^2)\cos^2(\theta/2)\right]$$

Longitudinally polarized target and unpolarized beam

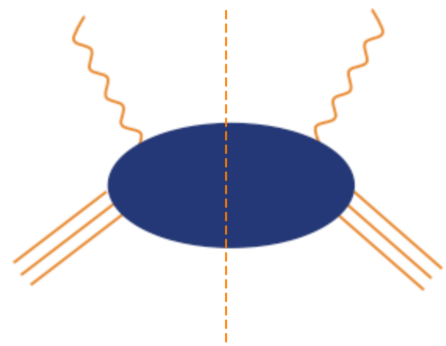
$$\left(\frac{d^2\sigma^{\downarrow\Uparrow}}{dE'd\Omega}+\frac{d^2\sigma^{\uparrow\Uparrow}}{dE'd\Omega}\right)=\frac{4\alpha^2}{Q^2}\frac{E}{E'}\left[(E+E'\cos\theta)G_1(x,Q^2)-Q^2G_2(x,Q^2)\right]$$

Transversely polarized target and unpolarized beam

$$\left(\frac{d^2\sigma^{\downarrow\Rightarrow}}{dE'd\Omega}+\frac{d^2\sigma^{\uparrow\Rightarrow}}{dE'd\Omega}\right)=\frac{4\alpha^2}{Q^2}\frac{E'^2}{E}\sin\theta\left[MG_1(x,Q^2)+2EG_2(x,Q^2)\right]$$

Virtual Photoabsorption Cross Section

$$\gamma^* + N \to \gamma^* + N$$



Compton scattering amplitude

$$\sigma_{\pm 1,0} = \frac{4\pi^2\alpha}{K}\epsilon^{\mu *}_{\pm 1,0} W_{\mu\nu}\epsilon^{\nu}_{\pm 1,0}$$

$$K = \nu - Q^2/2M$$

$$\epsilon_{\pm 1} = \frac{1}{\sqrt{2}}(0, 1, \pm i, 0)$$

Polarization vectors

$$\epsilon_0 = \frac{1}{\sqrt{Q^2}}(\sqrt{Q^2+\nu^2}, 0, 0, \nu)$$

$$\mathrm{Im}T_{[1,\frac{1}{2}\to 1,\frac{1}{2}]} \propto \sigma_{3/2} = \frac{4\pi^2\alpha}{K}[W_1 + M\nu G_1 - Q^2 G_2]$$

$$\mathrm{Im}T_{[1,-\frac{1}{2}\to 1,-\frac{1}{2}]} \propto \sigma_{1/2} = \frac{4\pi^2\alpha}{K}[W_1 - M\nu G_1 + Q^2 G_2]$$

$$\mathrm{Im}T_{[0,\frac{1}{2}\to 0,\frac{1}{2}]} \propto \sigma_L = \frac{4\pi^2\alpha}{K}[W_2(1+\nu^2/Q^2) - W_1]$$

$$\mathrm{Im}T_{0,-\frac{1}{2}\to 1,\frac{1}{2}} \propto \sigma_{TL} = \frac{4\pi^2\alpha}{K}\sqrt{Q^2}[M G_1 + \nu G_2]$$

Virtual Photoabsorption Cross Section

$$\sigma_T \equiv \frac{1}{2}(\sigma_{1/2} + \sigma_{3/2}) = \frac{4\pi^2\alpha}{K} W_1(\nu, Q^2)$$

$$\sigma_L \equiv \sigma_0 = \frac{4\pi^2\alpha}{K} \left[\left(1 + \frac{\nu^2}{Q^2}\right) W_2(\nu, Q^2) - W_1(\nu, Q^2) \right]$$

The unpolarized differential deep inelastic cross section can be expressed in terms of the virtual photoabsorption cross sections

$$\frac{d\sigma}{dE' d\Omega}|_{lab} = \Gamma\,(\sigma_T + \epsilon\sigma_L)$$

$$\Gamma = \frac{\alpha K}{2\pi^2 Q^2} \frac{E'}{E} \frac{1}{1-\epsilon} \qquad \epsilon = \left(1 + 2\frac{\nu^2 + Q^2}{Q^2}\tan^2\frac{\theta}{2}\right)^{-1}$$

The nucleon as a laboratory for QCD

- How to get Information about the nucleon structure?

  Nucleon static properties are well known, like
  - charge
  - mass
  - magnetic moment

  but it in terms of the constituents, quarks and gluons
- Elastic scattering
  - Charge distribution
  - Magnetization distribution
- Deep inelastic scattering
  - Momentum distribution among the different constituents
  - Charge distribution among the different constituents
  - Spin distribution among the different constituents

Proton

Mass:
$1.672\,621\,71(29) \times 10^{-27}$ kg
$938.272\,029(80)$ MeV/c^2
Electric Charge:
$1.602\,176\,53(14) \times 10^{-19}$ C
Diameter:
about 1.5×10^{-15} m
Spin:
1/2
Quark Composition:
1 down, 2 up

Scaling of structure functions

First measurements of the unpolarized cross section show that at large Q^2 the cross section was independent of Q^2

At large Q^2 and large ν but finite x the structure functions depend only one variable, x

$$\boxed{\begin{aligned} MW_1(\nu,Q^2) &\rightarrow F_1(x) \\ \nu W_2(\nu,Q^2) &\rightarrow F_2(x) \end{aligned}}$$

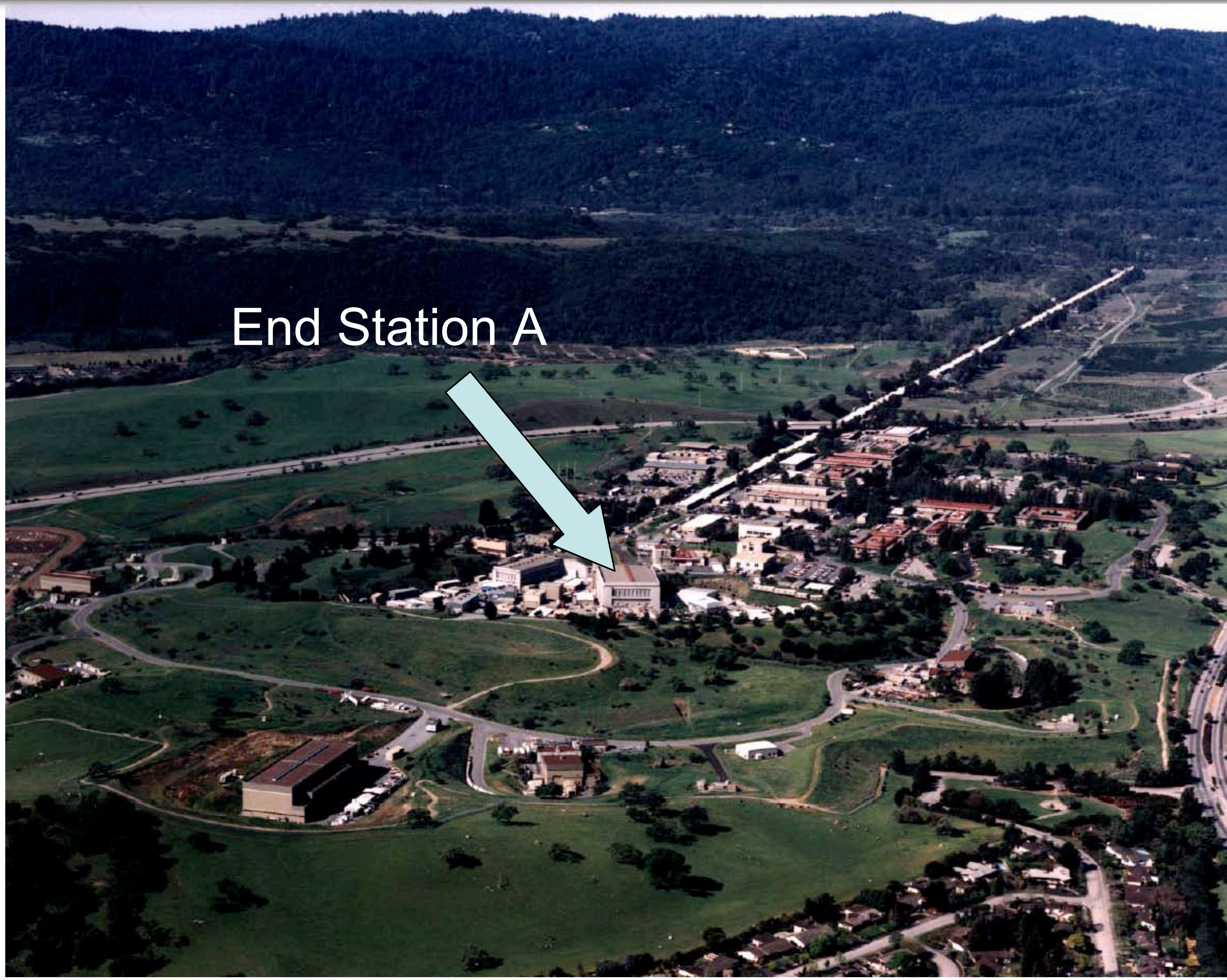
$$\begin{aligned} M^2\nu G_1(\nu,Q^2) &\rightarrow g_1(x) \\ M\nu^2 G_2(x,Q^2) &\rightarrow g_2(x) \end{aligned}$$

$$x = \frac{Q^2}{2M\nu}$$

The typical notation found in many papers is to write the cross sections in terms of

$$\boxed{F_1(x,Q^2), F_2(x,Q^2), g_1(x,Q^2) \ \text{ and } \ g_2(x,Q^2)}$$

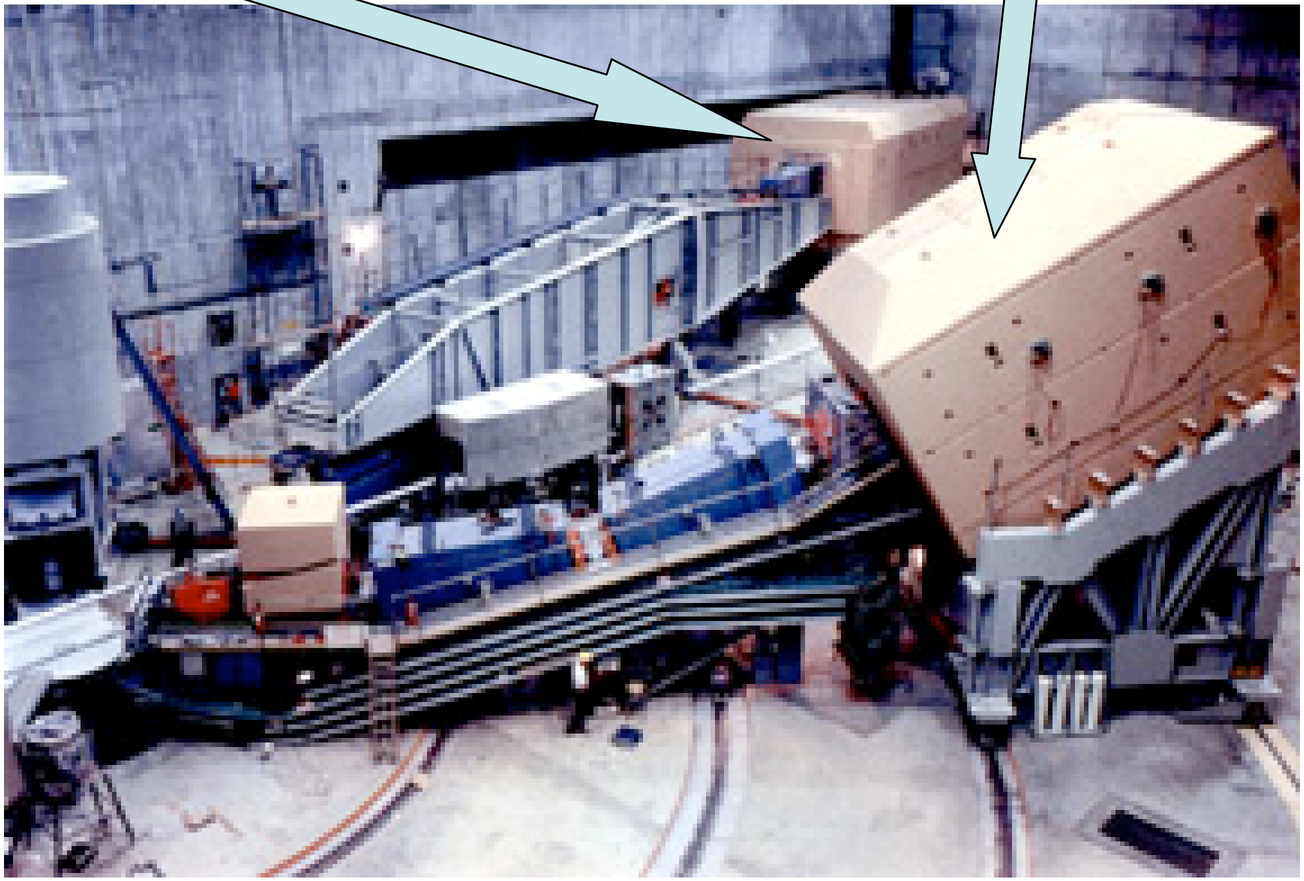
SLAC



SLAC End Station A Spectrometers

20 GeV maximum momentum spect.

8 GeV maximum momentum spect.



Scaling of F_2 Structure Function

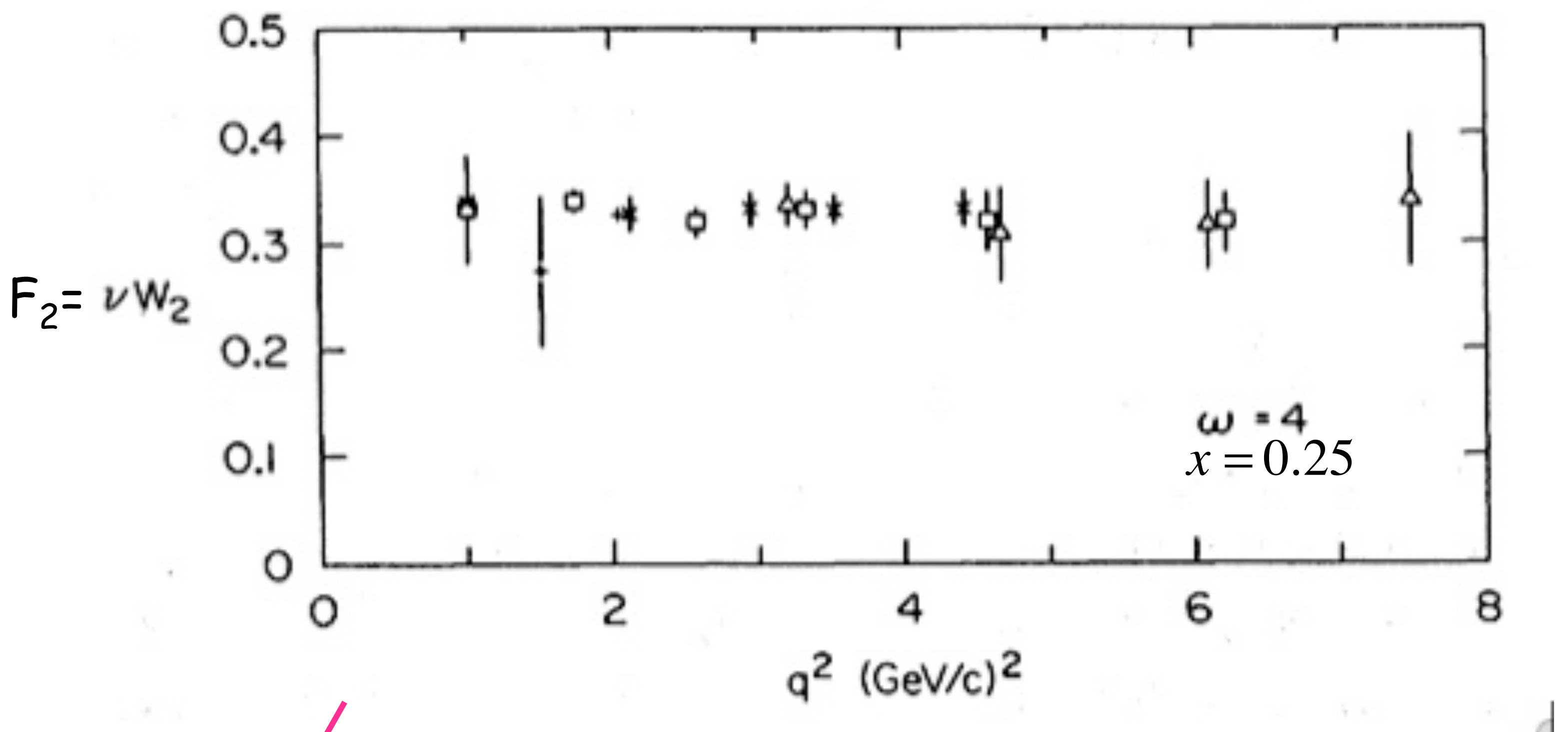


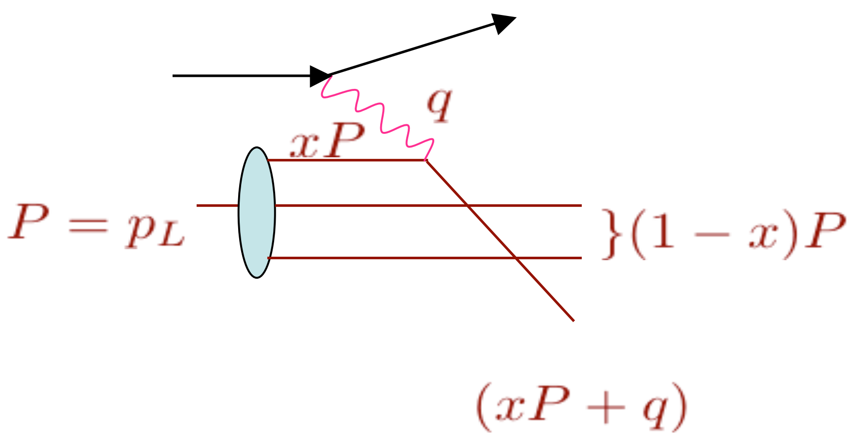
Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

1990 Nobel Prize

J. I. Friedman, H. W. Kendall and R. E. Taylor

Quark-Parton Model

Bjorken, Feynman and Paschos



The nucleon is made out of non-interacting point like particles called partons

The photon quark scattering is elastic scattering

Where x is the fraction of nucleon momentum carried by the struck quark

	Proton	Parton
	$\downarrow$	$\downarrow$
Energy	E	xE
Momentum	p_L	xp_L
	$p_T = 0$	$p_T = 0$
Mass	M	$m = (x^2E^2 - x^2p_L^2)^{1/2} = xM$

Quark Parton Model

$$(xP+q)^2 = m^2 \Rightarrow x^2P^2 + 2xP\cdot q + q^2 = m^2$$

At large q^2 assume $\quad q^2 \gg x^2P^2 \quad$ and $\quad q^2 \gg m^2$

thus $\quad 2xP\cdot q + q^2 \simeq 0$

solving for x in the Lab frame we obtain

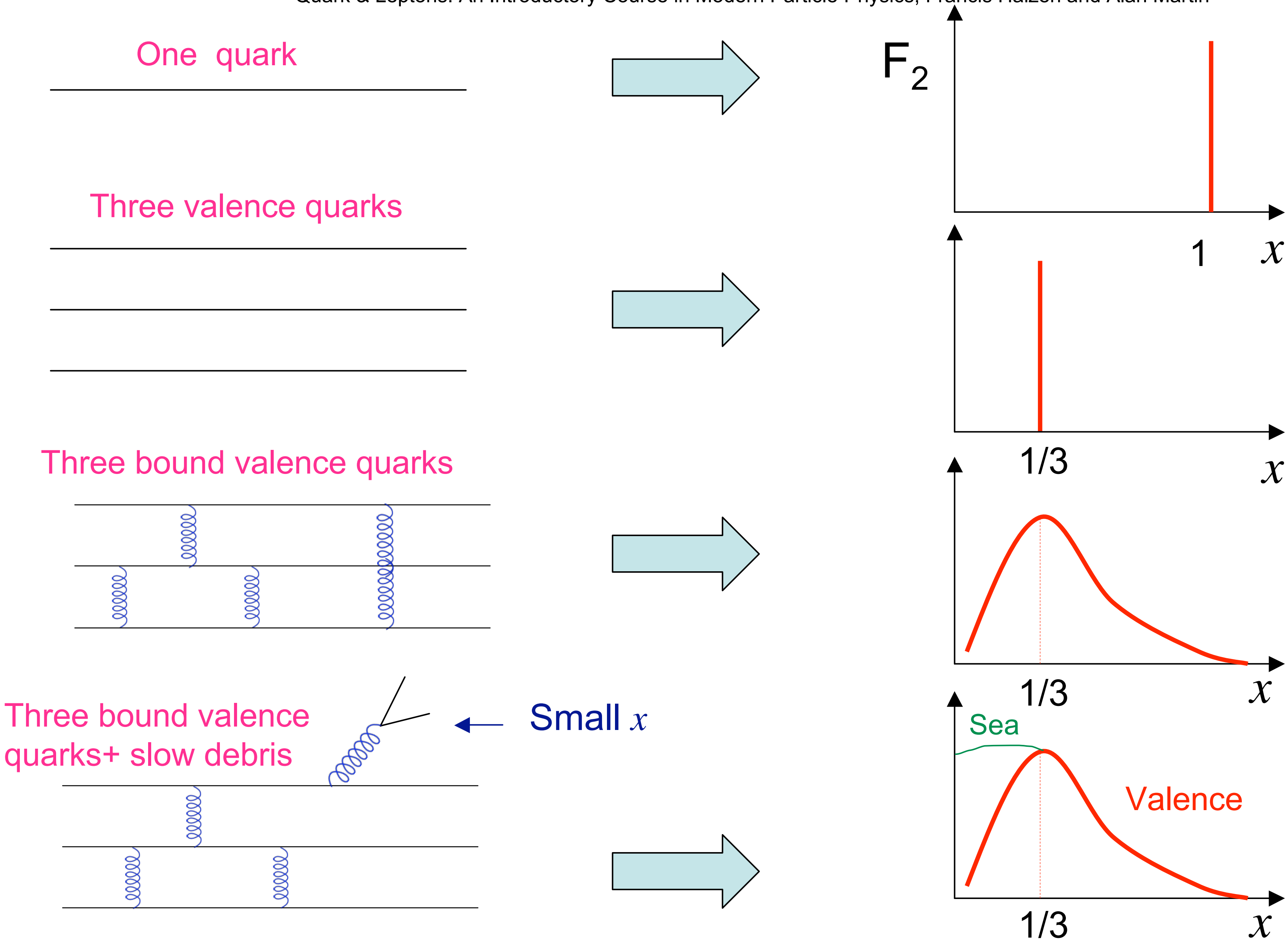
$$2xM\cdot\nu + q^2 = 0 \Rightarrow \boxed{x = \frac{Q^2}{2M\nu}}$$

Elastic scattering off a quark lead to $\quad q^2 = 2m\nu$

Then $\quad \boxed{x = \frac{m}{M}} \quad$ Fraction of nucleon mass carried by struck quark !?

A scattering picture of the proton

Quark & Leptons: An Introductory Course in Modern Particle Physics, Francis Halzen and Alan Martin



Structure functions in the parton model

In the infinite-momentum frame:

- no time for interactions between partons
- Partons are point-like non-interacting particles: $\sigma_{Nucleon} = \Sigma_i \sigma_i$

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 [q_i^{\uparrow}(x) + q_i^{\downarrow}(x)]$$

$$F_2(x) = \sum_i e_i^2 x [q_i^{\uparrow}(x) + q_i^{\downarrow}(x)]$$

$$2xF_1(x) = F_2(x) = \sum_i e_i^2 x q_i(x)$$

Callan-Gross relation $\quad \frac{\sigma_L}{\sigma_T} \to 0$

It is a consequence of quarks having a spin 1/2

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 [q_i^{\uparrow}(x) - q_i^{\downarrow}(x)]$$

$g_2(x)$ has no simple partonic interpretation.
It involves quark-gluon interactions

Useful relations among quark distributions

$$\frac{1}{x}F_2^p(x) = \left(\frac{2}{3}\right)^2\left[u^p(x)+\bar{u}^p(x)\right]+\left(\frac{1}{3}\right)^2\left[d^p(x)+\bar{d}^p(x)\right]$$
$$+\left(\frac{1}{3}\right)^2\left[s^p(x)+\bar{s}^p(x)\right]$$

$$\frac{1}{x}F_2^n(x) = \left(\frac{2}{3}\right)^2\left[u^n(x)+\bar{u}^n(x)\right]+\left(\frac{1}{3}\right)^2\left[d^n(x)+\bar{d}^n(x)\right]$$
$$+\left(\frac{1}{3}\right)^2\left[s^n(x)+\bar{s}^n(x)\right]$$

- The proton and neutron are members of an isopin doublet therefore there are as many u quarks in the proton as d quarks in the neutron

$$u^p(x)=d^n(x)\equiv u(x)$$
$$d^p(x)=u^n(x)\equiv d(x)$$
$$s^p(x)=s^n(x)\equiv s(x)$$

Nucleon quark distributions

Kuti and Weisskopf or Landshoff and Polkinghorne 1971

Separate "valence" and "sea"

$$u(x) = u_v(x) + u_s(x)$$

$$d(x) = d_v(x) + d_s(x)$$

The "sea" is common to all quark flavors

$$u_s(x) = \bar{u}_s(x) = d_s(x) = \bar{d}_s(x) = s_s(x) = \bar{s}_s(x) = S(x)$$

If we rewrite F_2 for the proton and neutron using the new relations we obtain

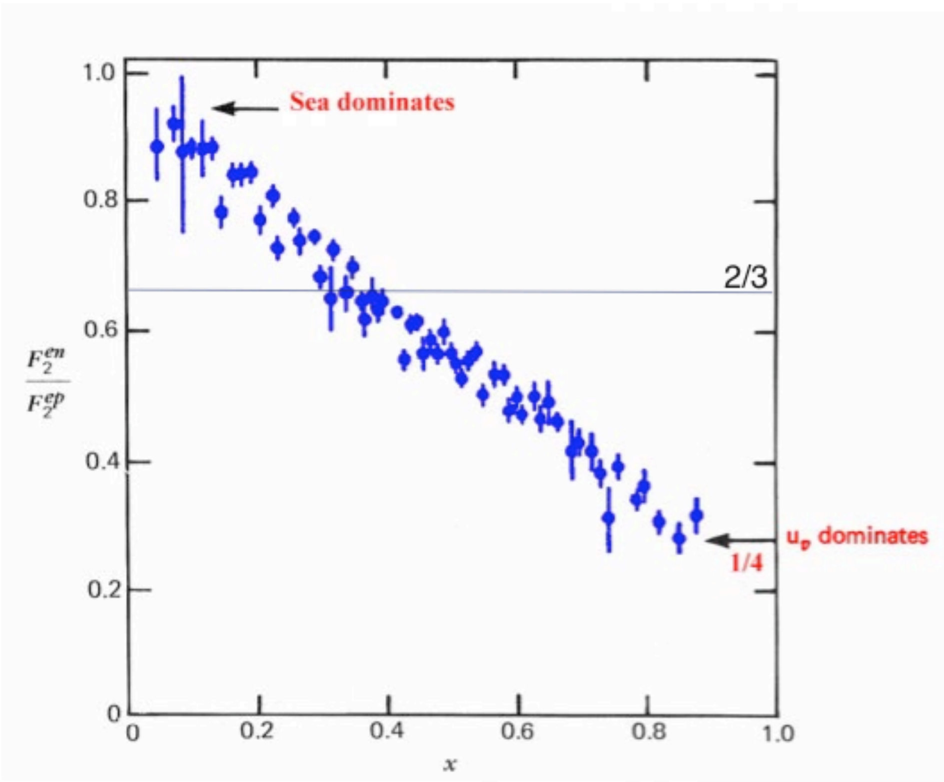
$$\left.\begin{aligned} \frac{1}{x}F_2^p(x) &= \frac{1}{9}\left[4u_v(x) + d_v(x)\right] + \frac{4}{3}S(x) \\ \frac{1}{x}F_2^n(x) &= \frac{1}{9}\left[u_v(x) + 4d_v(x)\right] + \frac{4}{3}S(x) \end{aligned}\right\} \quad \frac{F_2^n(x)}{F_2^p(x)} = \frac{u_v + 4d_v + 12S}{4u_v + d_v + 12S}$$

Towards the nucleonquark distributions

$$\frac{F_2^n(x)}{F_2^p(x)} \xrightarrow[x \to 1]{} \frac{u_v + 4d_v}{4u_v + d_v}$$

$$\frac{F_2^n(x)}{F_2^p(x)} \xrightarrow[x \to 0]{} 1$$

- When probing the small x momenta of quarks we expect that the struck quark with small x is part of the "sea pairs".
  - In this case we expect the neutron or proton to respond similarly.
  - This is confirmed by experiment
- When probing the large x momenta of quarks we expect the valence struck quark to dominate leaving little momentum to sea pairs

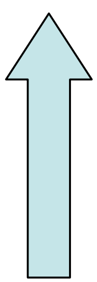


Constituent quark Model

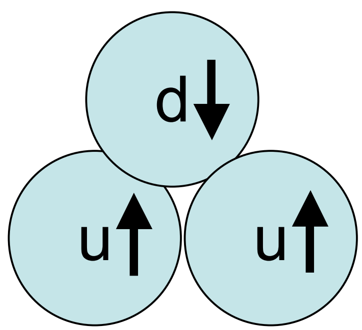
- Static symmetric wave function: SU(6)=SU(3)$\otimes$SU(2) (Flavor: SU(3), Spin: SU(2))

$$
\begin{aligned}
|p^{\uparrow}\rangle = \; & \sqrt{\tfrac{1}{18}} \; \left[-2\,|u^{\uparrow}u^{\uparrow}d^{\downarrow}\rangle - 2\,|u^{\uparrow}d^{\downarrow}u^{\uparrow}\rangle - 2\,|d^{\downarrow}u^{\uparrow}u^{\uparrow}\rangle\right. \\
+ \; & |u^{\uparrow}u^{\downarrow}d^{\uparrow}\rangle + |u^{\uparrow}d^{\uparrow}u^{\downarrow}\rangle + |d^{\uparrow}u^{\uparrow}u^{\downarrow}\rangle \\
+ \; & \left.|u^{\downarrow}u^{\uparrow}d^{\uparrow}\rangle + |u^{\downarrow}d^{\uparrow}u^{\uparrow}\rangle + |d^{\uparrow}u^{\downarrow}u^{\uparrow}\rangle\right]
\end{aligned}
$$

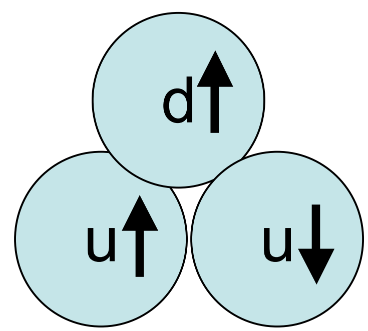
Square it…



Proton Spin



$$\frac{2}{3}$$



$$\frac{1}{3}$$

Constituent quark model

$u^{\uparrow}$ quark %

$$P(u^{\uparrow}) = \frac{2}{3}\cdot\frac{2}{3} + \frac{1}{3}\cdot\frac{1}{3}$$

Left picture

Right picture

$u^{\uparrow}$ quark %

$$\boxed{P(u^{\uparrow}) = \frac{5}{9}}$$

$$\boxed{P(d^{\uparrow}) = \frac{1}{9}}$$

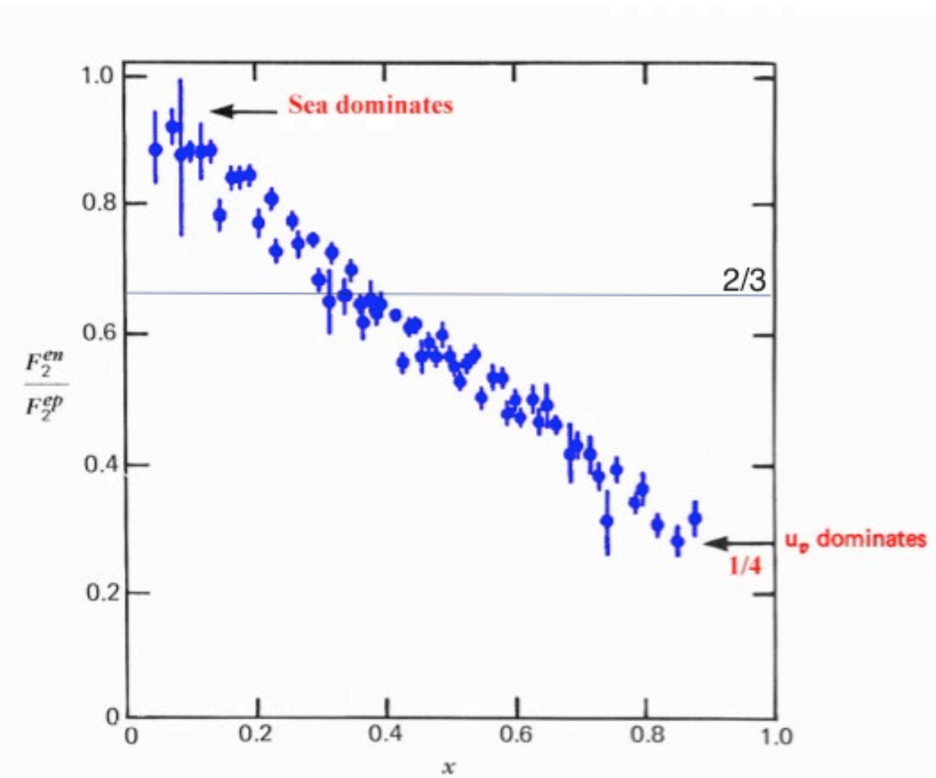
$$\boxed{P(u^{\downarrow}) = \frac{1}{9}}$$

$$\boxed{P(d^{\downarrow}) = \frac{2}{9}}$$

SU(6) symmetry breaking

Plugging the previous numbers we obtain

$$\frac{F_2^n(x)}{F_2^p(x)} \xrightarrow[x \to 1]{} \frac{u_v + 4d_v}{4u_v + d_v} \quad \Longrightarrow \quad \frac{F_2^n}{F_2^P} = \frac{2/3 + 4 \times 1/3}{4 \times 2/3 + 1/3} = \frac{2}{3}$$



- Clearly SU(6) symmetry is broken

- Writing a wavefunction that would favor the dominance of the up quark goes towards reproducing the experimental data

$$\frac{F_2^n(x)}{F_2^p(x)} \xrightarrow[x \to 1]{} \frac{1}{4}$$

F2 proton - F2 neutron

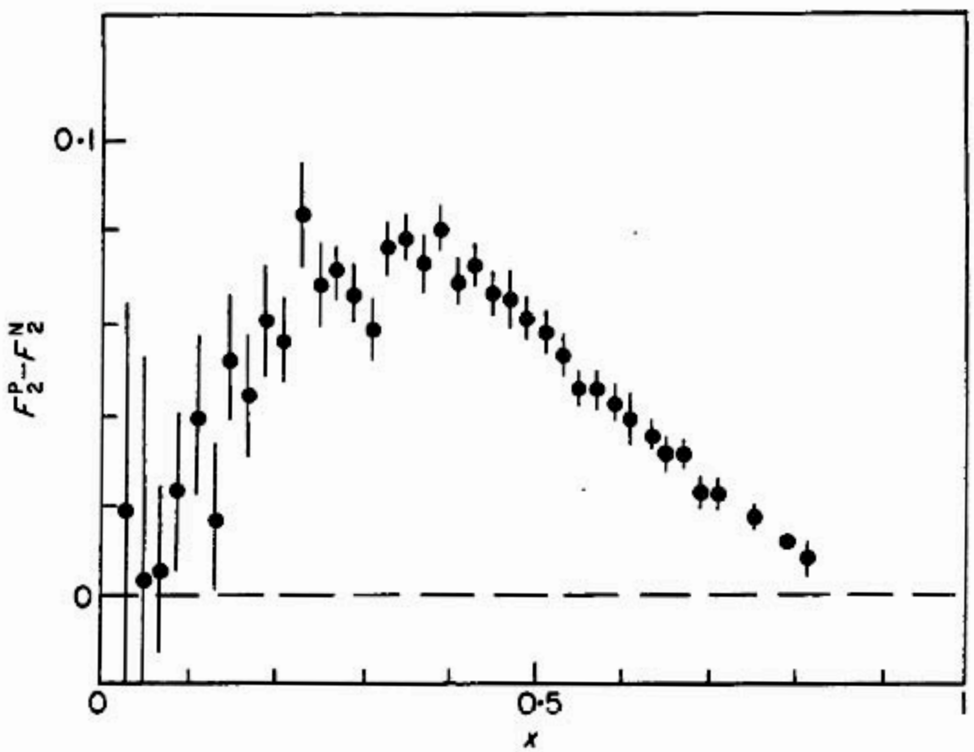
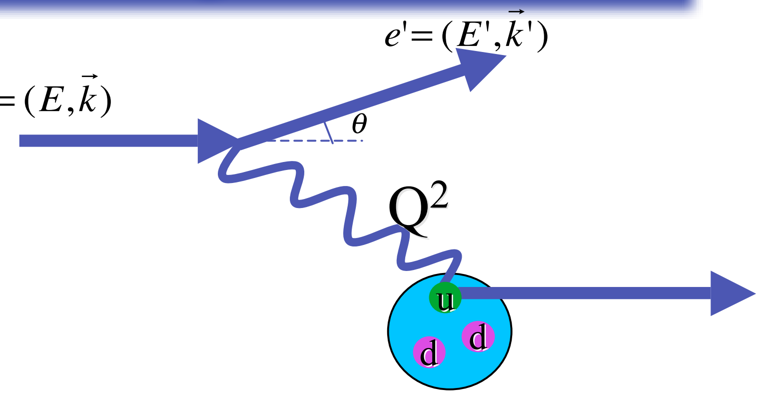


FIG. 11.6. $\nu W_2(\text{ep}) - \nu W_2(\text{en})$ data as a function of x.

$$F_2^p(x) - F_2^n(x) = \frac{x}{3}\left[u_v(x) - d_v(x)\right]$$

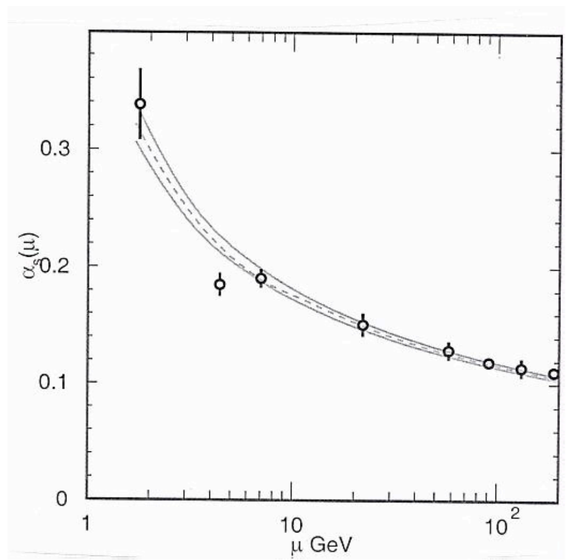
Deep Inelastic Scattering in QCD

- The strong running coupling constant becomes small at large Q^2



- The theory can be solved using perturbation theory techniques (pQCD)

- Scaling is predicted but something more too, evolution of the structure functions thus violation of scaling at finite Q^2



High Q^2 and W>2GeV: fine resolution → we see partons

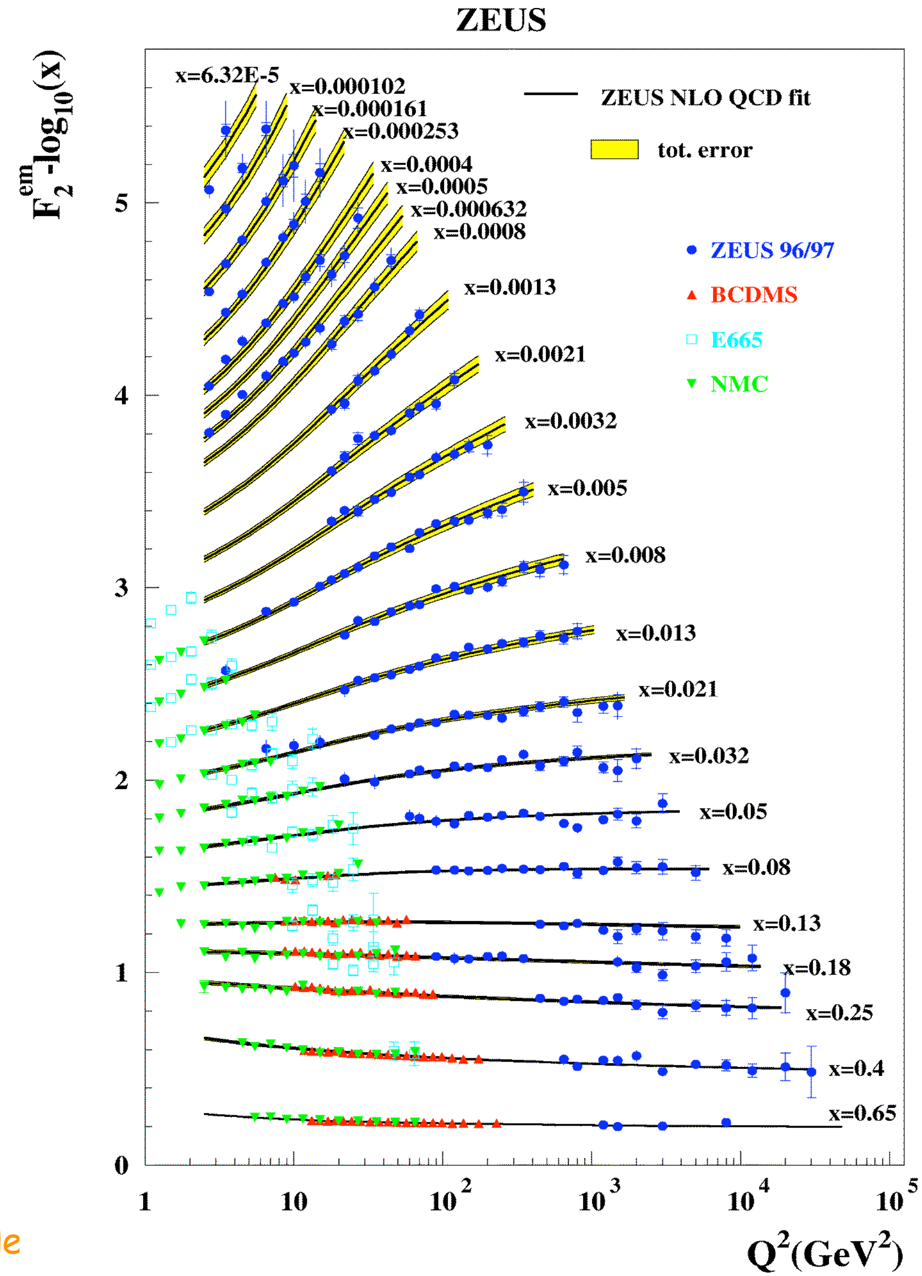
→ scaling → asymptotic freedom of the strong interaction

2004 Nobel Prize

D. J. Gross, H. D. Politzer and F. Wilczek

Measurements at HERA; ZEUS detector

- We observe scaling in the large x range (x~0.1 to 0.6)
- There are also clear violations of scaling
- Violations are well understood with perturbative QCD (pQCD)
- Measurements on a hydrogen (proton) and deuterium targets (neutron) help determine the quark distribution functions

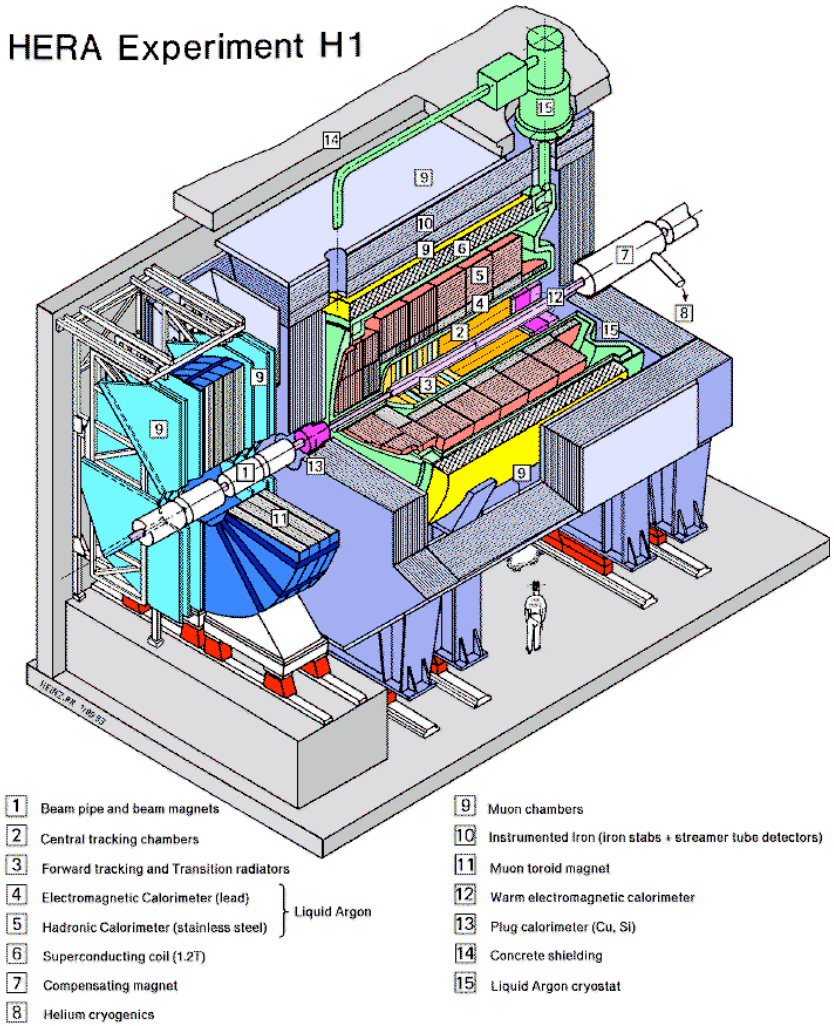


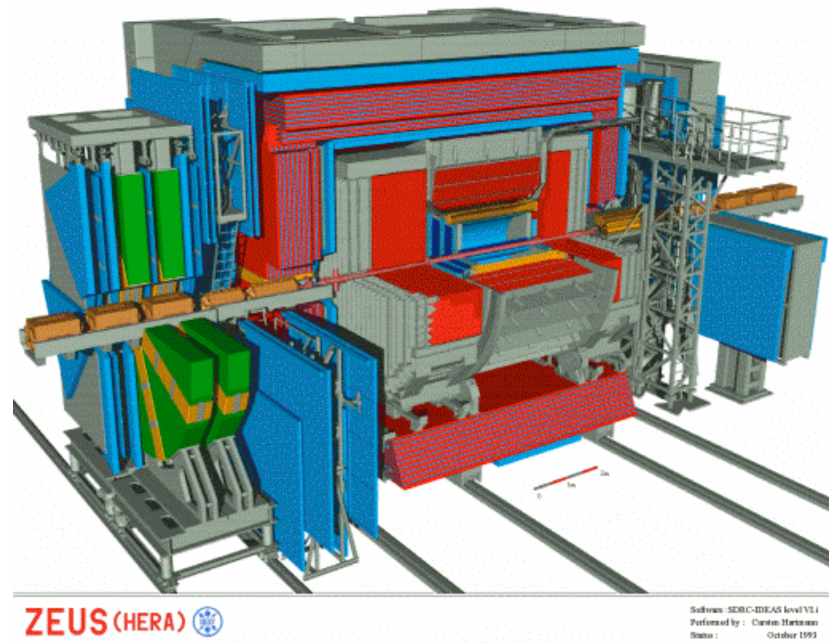
A bird's eye view of the DESY site and the surroundings in Hamburg

- HERA, with its circumference of 6.3 km is the biggest accelerator at DESY and it is housed in a tunnel with an inner diameter of 5.2 m which is situated about 10-20 m underground

- 920 GeV protons collide with electrons or positrons with an energy of 27.5 GeV thereby providing a way to study the inner structure of protons.

The H1 and ZEUS detectors at DESY





PDFs in the valence quark region

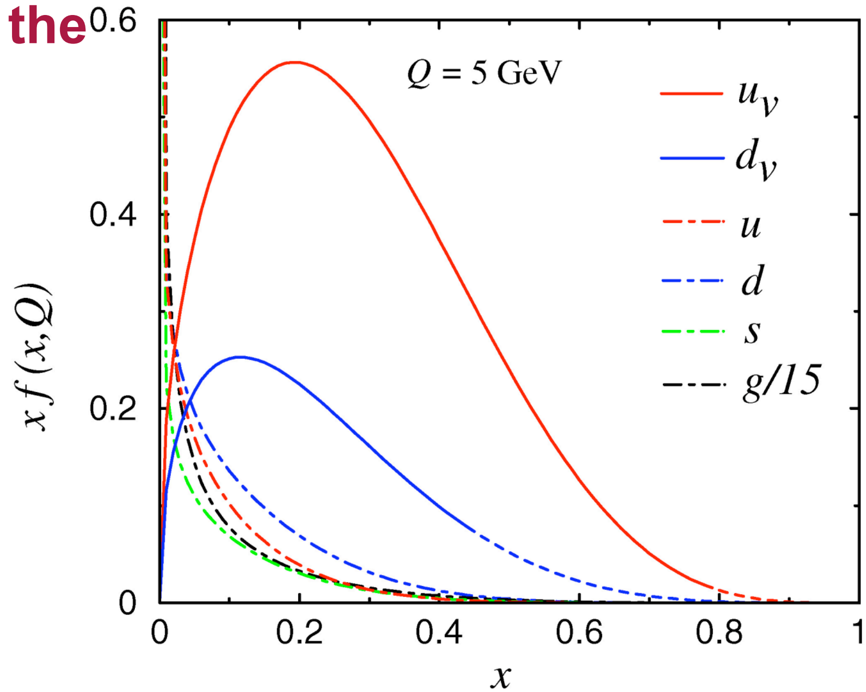
Understand the nucleon structure in the valence quark region

⊙ What is required?

➥ Complete knowledge of parton distribution functions (PDFs).

At Large x

- large x exposes valence quarks - free of sea effects
- no explicit hard gluons to be included



- x->1 behavior – sensitive test of spin-flavor symmetry breaking

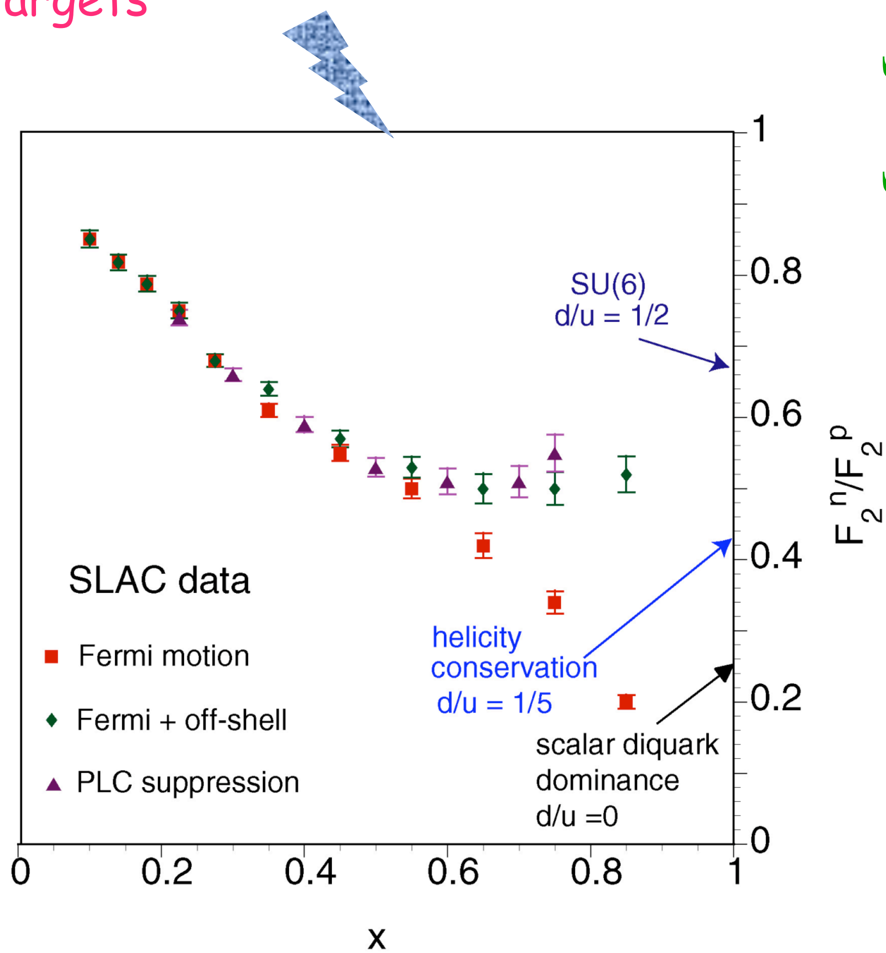
$$M_n(Q^2) = \int_0^1 dx\; x^{n-1}\, g_1(x, Q^2), \qquad n = 1, 3, 5...$$

- important for higher moments of PDFs - compare with lattice QCD

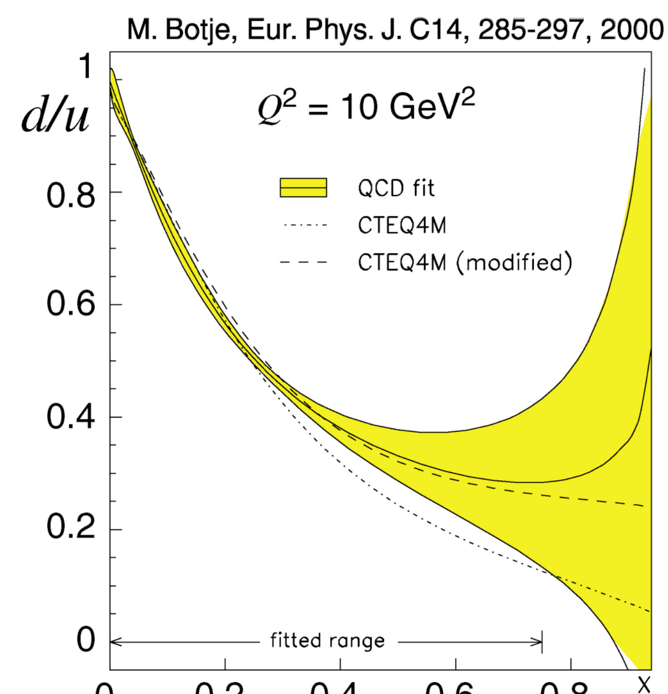
- intimately related with resonances, quark-hadron duality

Unpolarized Neutron to Proton ratio

- In the large x region (x>0.5) the ratio F_2^n/F_2^p is not well determined due to the lack of free neutron targets



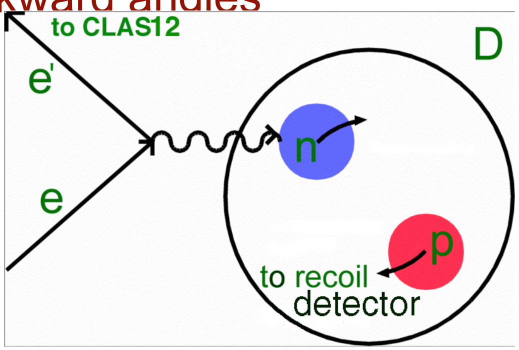
- Impact:
  - determine valence *d* quark momentum distribution
  - extract helicity dependent quark distributions through inclusive DIS
  - high x and Q^2 background in high energy particle searches.
  - construct moments of structure functions



Unpolarized Neutron to Proton ratio

Spectator tagging

- Nearly free neutron target by tagging low-momentum proton from deuteron at backward angles



- Small p (70-100 MeV/c)
  - Minimize on-shell extrapolation (neutron only 7 MeV off-shell)
- Backward angles (θ_{pq}> 110°)
  - Minimize final state interactions

DIS from A=3 nuclei

- Mirror symmetry of A=3 nuclei
  - Extract F_2^n/F_2^p from ratio of ^{3}He/^{3}H structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

  - Super ratio

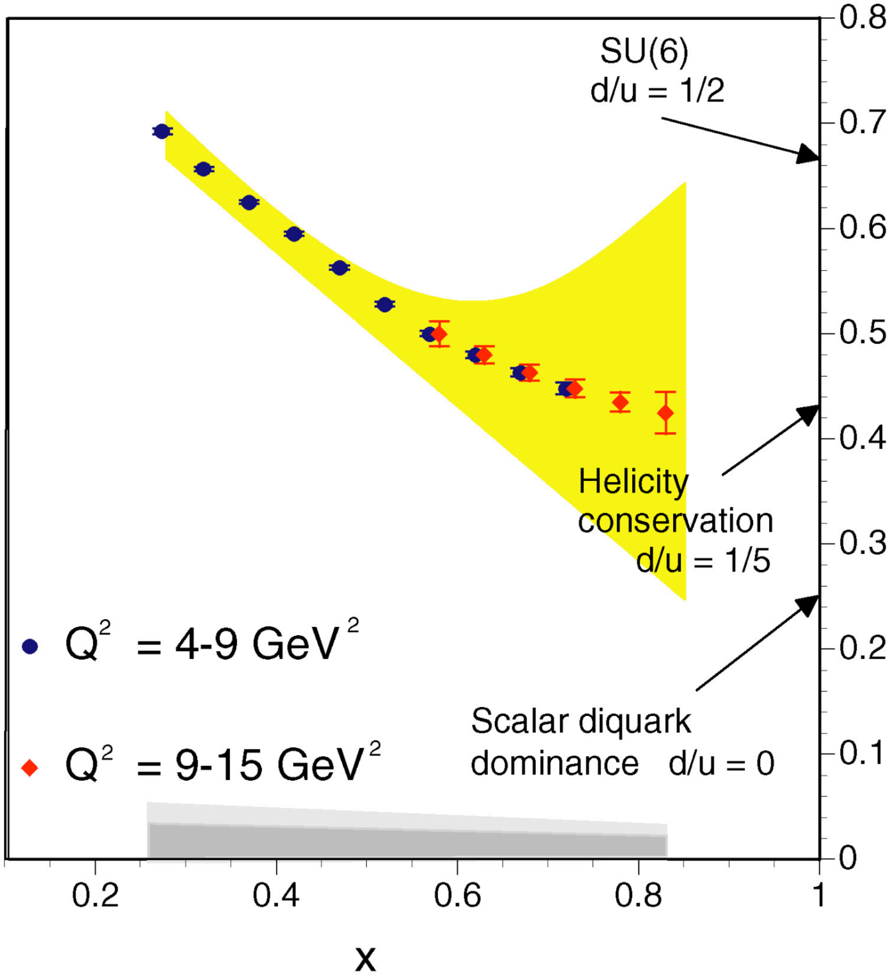
    $\mathcal{R}$ = ratio of "EMC ratios" for ^{3}He and ^{3}H

    calculated to within 1%

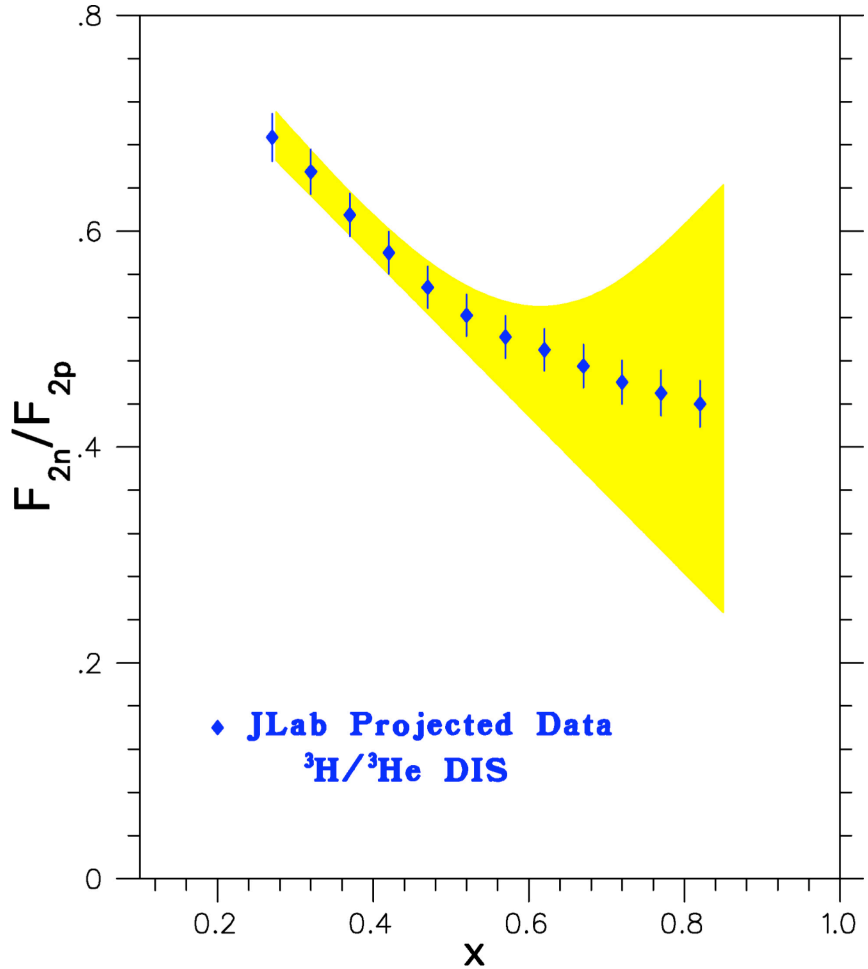
- Most systematic and theoretical uncertainties cancel

Unpolarized Neutron to Proton Ratio

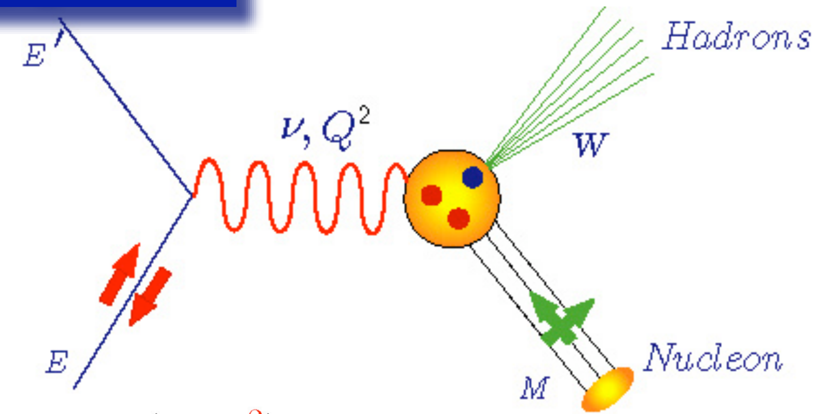
HallB 11 GeV with CLAS12



Hall C 11 GeV with HMS



Inclusive DIS



- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$
  - Proton & neutron measurements provide d/u distributions ratio

U $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

- Polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$
  - Proton & neutron measurements combined with d/u provide the spin-flavor distributions $\Delta u/u$ & $\Delta d/d$

Q^2 : Four-momentum transfer
x : Bjorken variable
ν : Energy transfer
M : Nucleon mass
W : Final state hadrons mass

L $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right]$$

T $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2E g_2(x,Q^2)\right]$$

Virtual photon-nucleon asymmetries

Longitudinal

$$\frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\uparrow\Uparrow}} = A_\parallel = D(A_1 + \eta A_2)$$

Transverse

$$\frac{\sigma^{\downarrow\Leftarrow} - \sigma^{\uparrow\Leftarrow}}{\sigma^{\downarrow\Leftarrow} + \sigma^{\uparrow\Leftarrow}} = A_\perp = d(A_1 - \xi A_2)$$

D, d, η and ξ are kinematic factors

D depends on $R(x, Q^2) = \sigma_L / \sigma_T$

$$A_1 = \frac{g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)}{F_1(x, Q^2)}$$

$$A_2 = \frac{\gamma[g_1(x, Q^2) + g_2(x, Q^2)]}{F_1(x, Q^2)}$$

where $\gamma = \sqrt{Q^2}/\nu$

- Positivity constraints

$|A_1| \leq 1$ and $|A_2| \leq \sqrt{R(1+ A_1)/2}$

In the quark-parton model:

$$F_1(x,\, Q^2) = \frac{1}{2}\sum_f e_f^2\, q_f(x,\, Q^2) \qquad g_1(x,\, Q^2) = \frac{1}{2}\sum_f e_f^2\, \Delta q_f(x,\, Q^2)$$

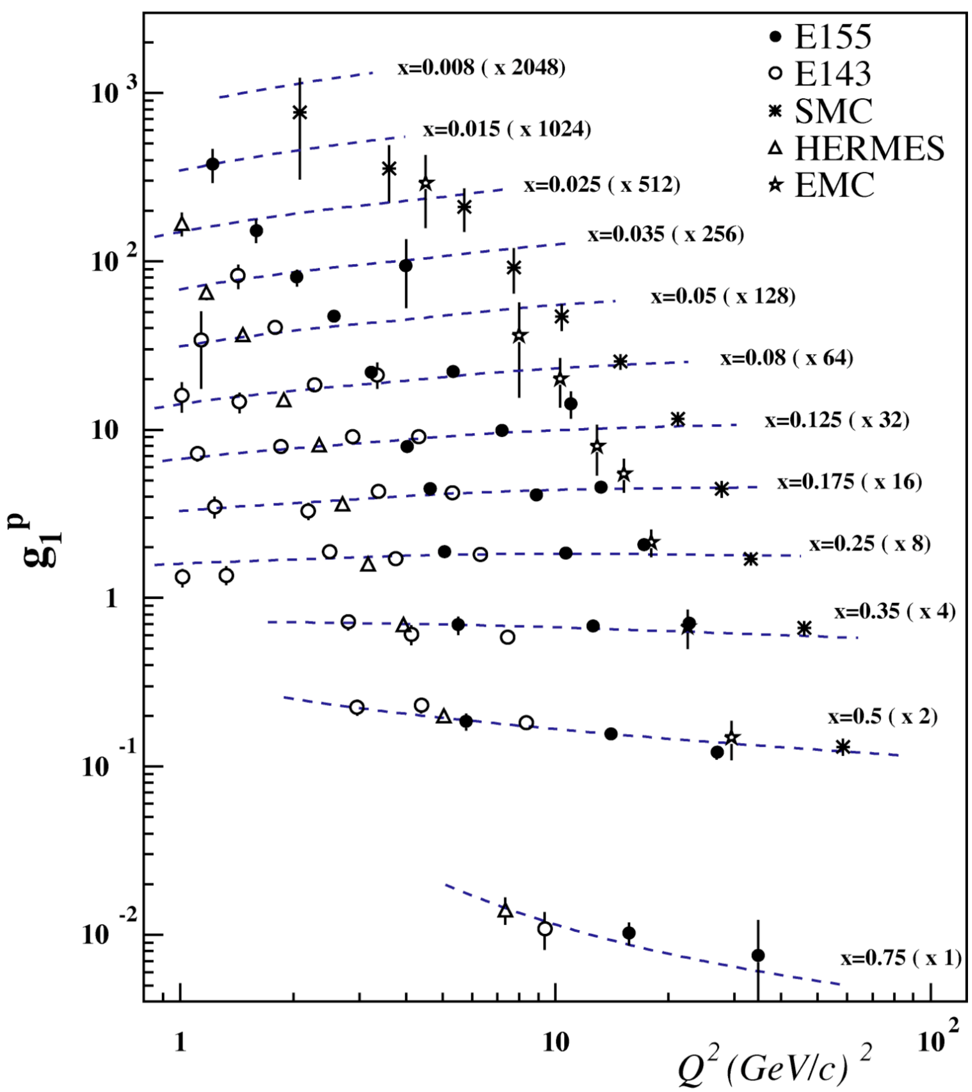
$$q_f(x) = q_f^{\uparrow}(x) + q_f^{\downarrow}(x) \qquad \Delta q_f(x) = q_f^{\uparrow}(x) - q_f^{\downarrow}(x)$$

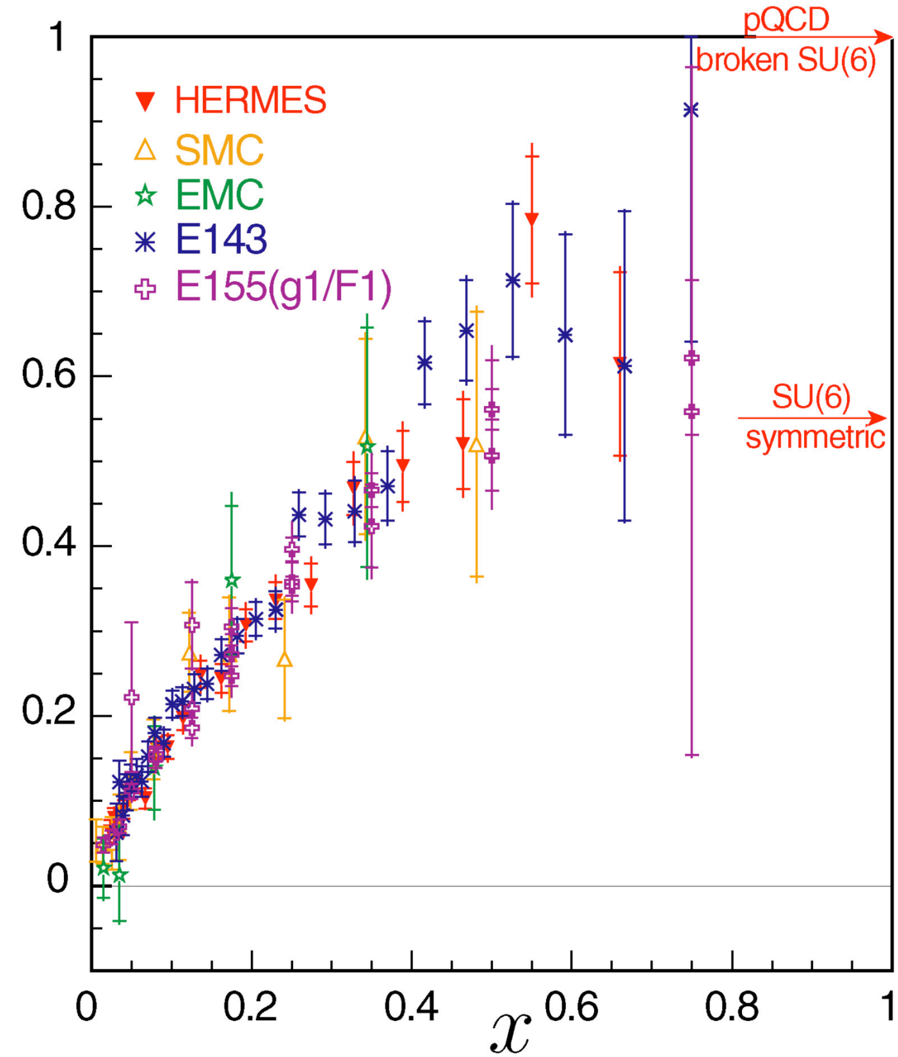
$q_f(x)$ quark momentum distributions of flavor f

$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

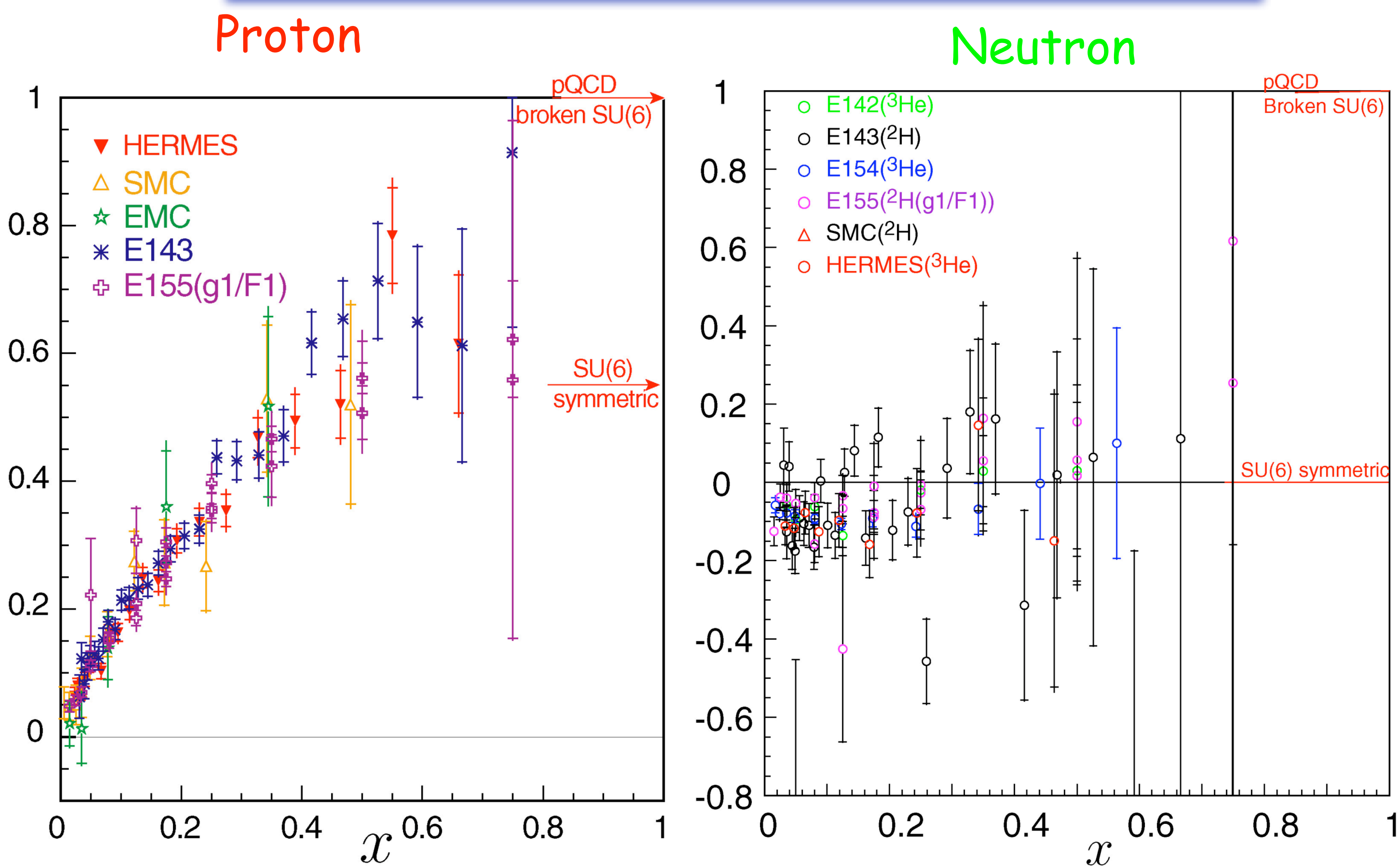
Examples of existing data and physics issues

World data on g_1^p





World data for A_1



SU(6) Breaking mechanism

- Relativistic Constituent Quark Model (CQM) — Close, Thomas, Isgur
  - Introduce hyperfine $\vec{S}_i \cdot \vec{S}_j \delta^3(\vec{r}_{ij})$ interaction (N - Δ mass splitting, etc...)
  - Constrain d/u using R^{np} data : $d(x)/u(x) = (4R^{np} - 1)/(4 - R^{np})$

$$|n\uparrow\rangle = \frac{1}{\sqrt{2}}|d\uparrow(du)_{000}\rangle$$

Dominant component

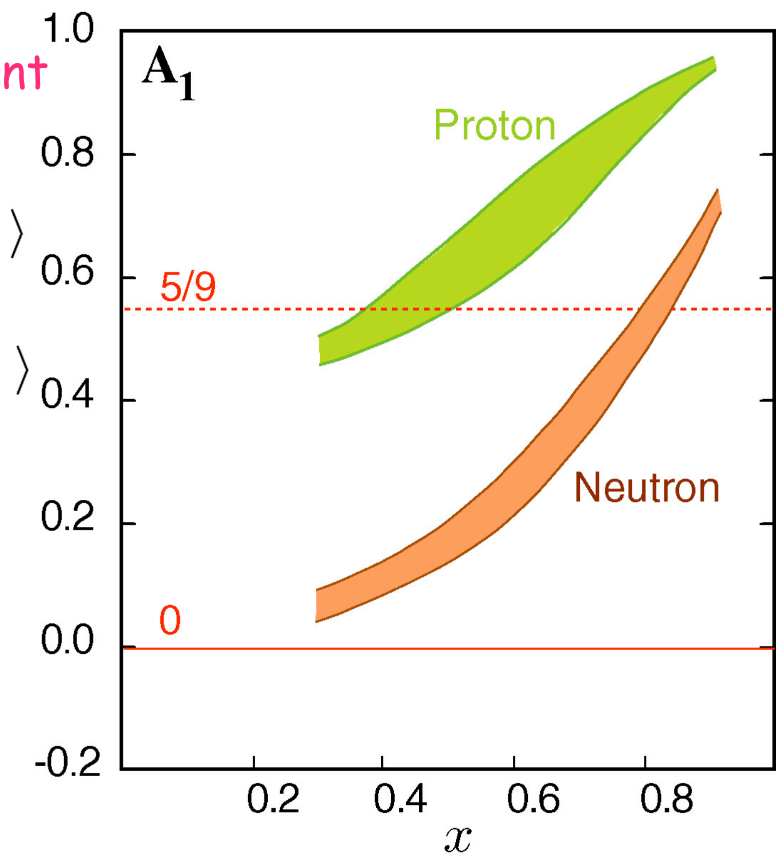
$$+\frac{1}{\sqrt{18}}|d\uparrow(du)_{110}\rangle - \frac{1}{3}|d\downarrow(du)_{111}\rangle$$

$$-\frac{1}{3}|u\uparrow(dd)_{110}\rangle + \frac{\sqrt{2}}{3}|u\downarrow(dd)_{111}\rangle$$

As x-->1

$A_1^p \to 1$ $A_1^n \to 1$ $d/u \to 0$

$\Delta u/u \to 1$ $\Delta d/d \to -1/3$



Perturbative gluon exchange

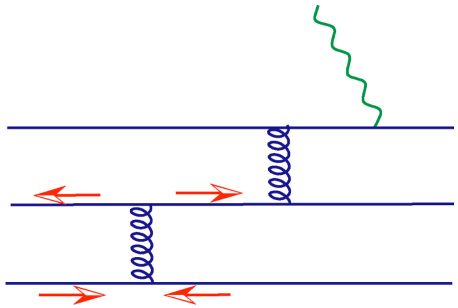
Farrar & Jackson, P.R.L. 35 (1975) 1416;
Brodsky et al., Nuc. Phys. B441 (1995) 197.

As x-->1

$A_1^p \rightarrow 1$ $A_1^n \rightarrow 1$ $d/u \rightarrow 1/5$

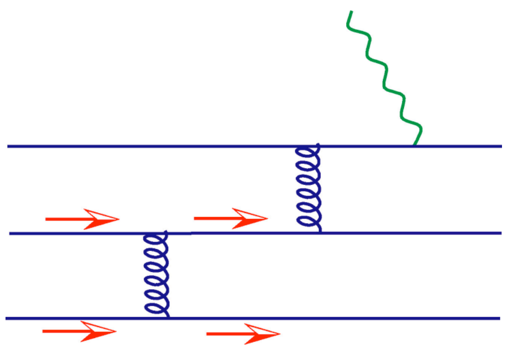
$\Delta u/u \rightarrow 1$ $\Delta d/d \rightarrow 1$

$S_z = 0$ {

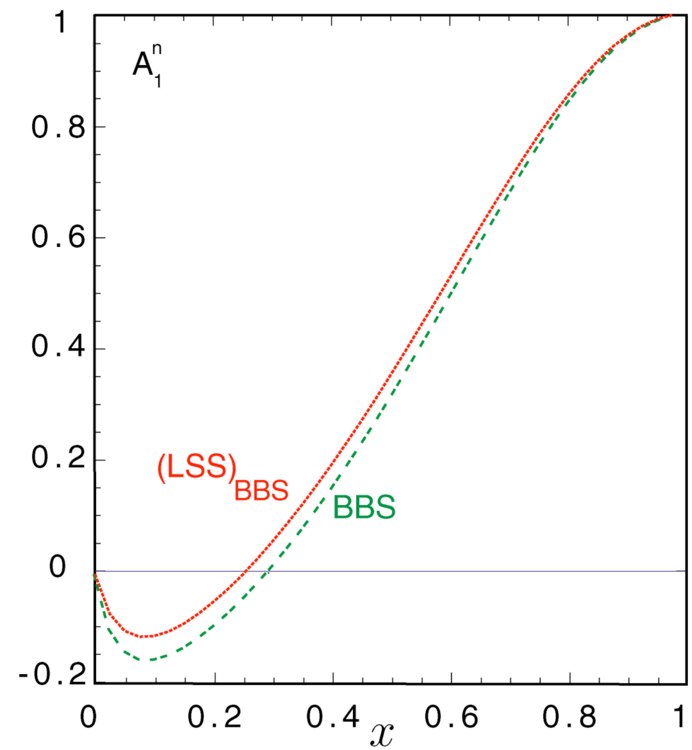


Can exchange transverse gluon- flipping both spins

$S_z = 1$ {



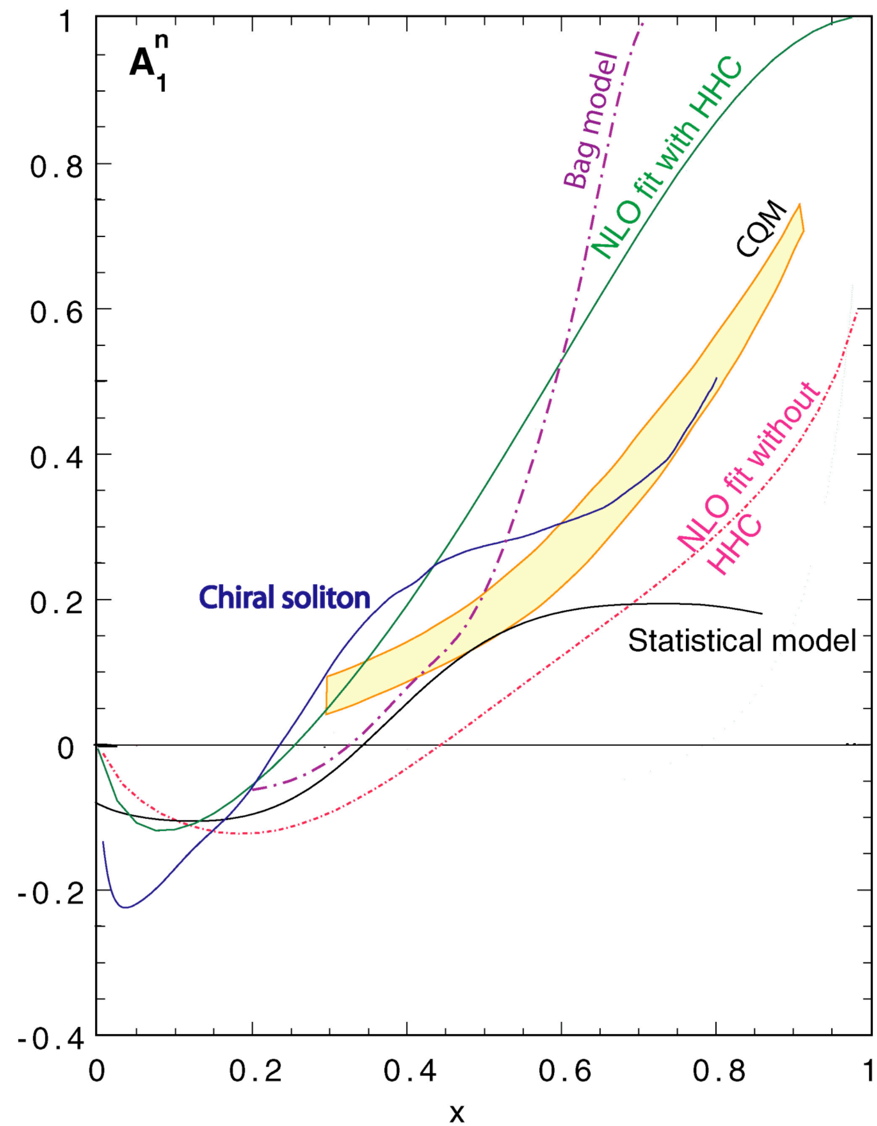
Only longitudinal gluons- cannot flip spins



Polarized quarks as x--> 1

- SU(6) symmetry:
  - $A_1^p = 5/9$ $A_1^n = 0$ $d/u=1/2$
  - $\Delta u/u = 2/3$ $\Delta d/d = -1/3$
- Broken SU(6) via scalar diquark dominance
  - $A_1^p \rightarrow 1$ $A_1^n \rightarrow 1$ $d/u \rightarrow 0$
  - $\Delta u/u \rightarrow 1$ $\Delta d/d \rightarrow -1/3$
- Broken SU(6) via helicity conservation
  - $A_1^p \rightarrow 1$ $A_1^n \rightarrow 1$ $d/u \rightarrow 1/5$
  - $\Delta u/u \rightarrow 1$ $\Delta d/d \rightarrow 1$

Note that $\Delta q/q$ as x--> 1 is more sensitive to spin-flavor symmetry breaking effects than A_1

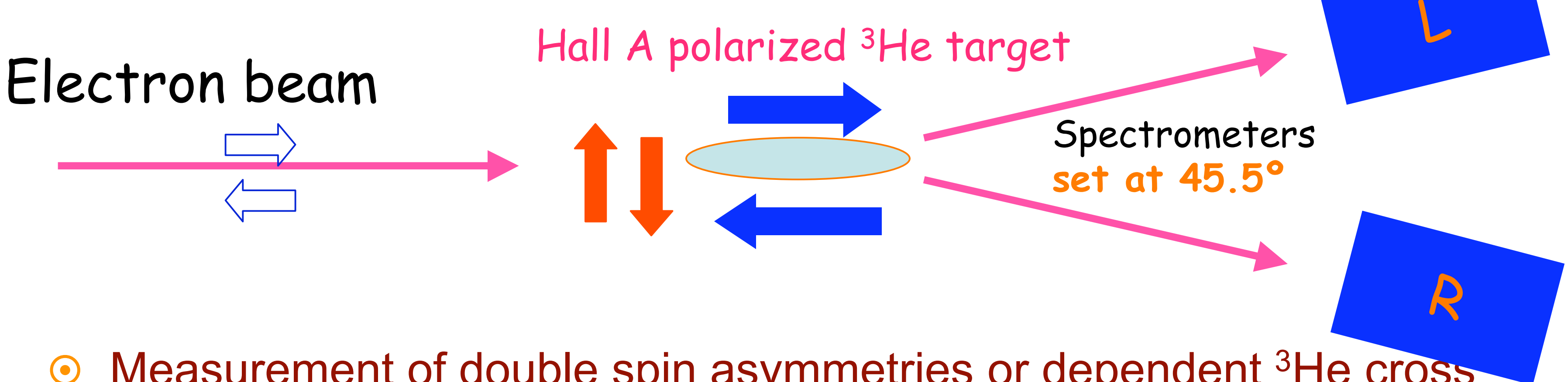


Tools: Hall A at Jefferson Lab

Polarized beam
- Energy: 0.86-5.1 GeV
- Polarization: > 70%
- Average Current: 5 to 15 μA

Hall A polarized ^3He target
- Pressure ~ 10 atm
- Polarization average: 35%
- Length: 40 cm with 100 μm thickness

Highest polarized luminosity~ $10^{36} cm^{-2}s^{-1}$

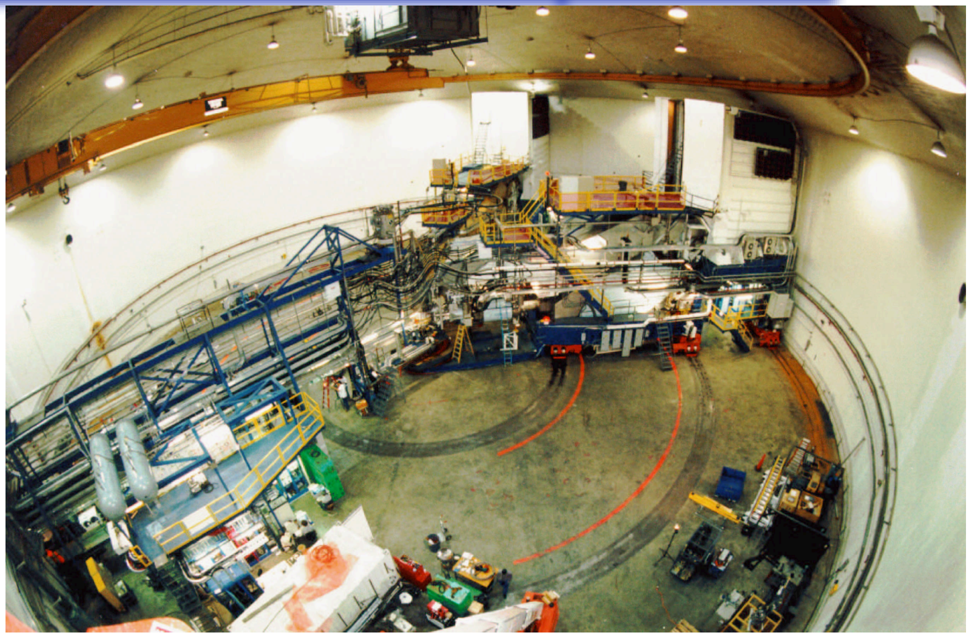


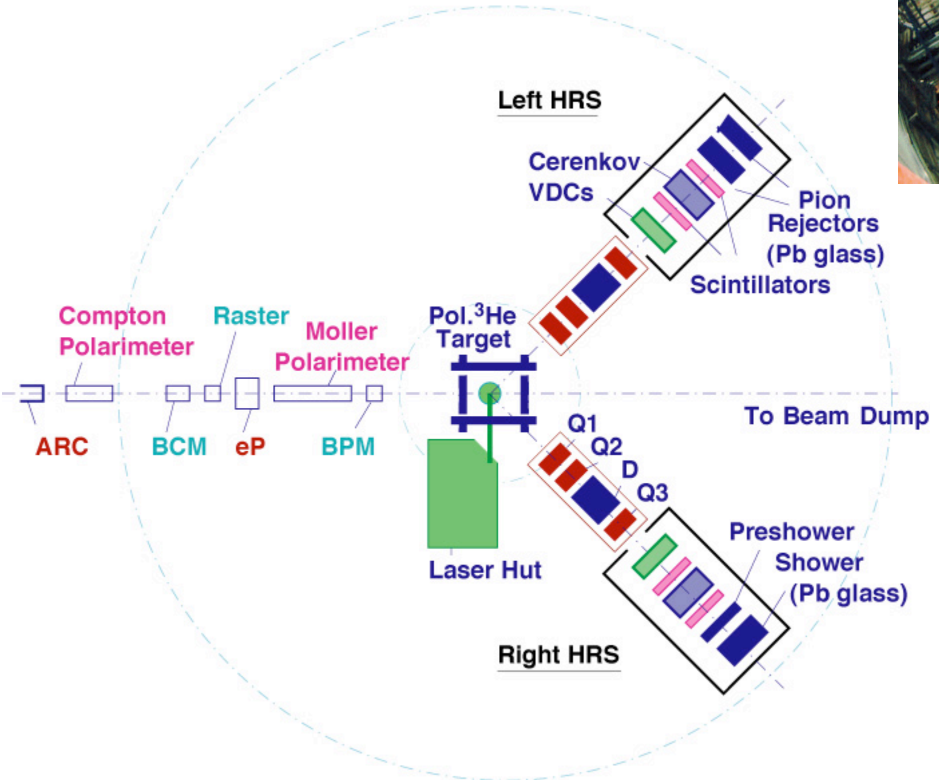
- Measurement of double spin asymmetries or dependent ^3He cross sections
- Extract g_1 spin structure functions of ^3He and neutron
- Extract moments of spin structure functions of the neutron.

Jlab Hall A Experimental Setup

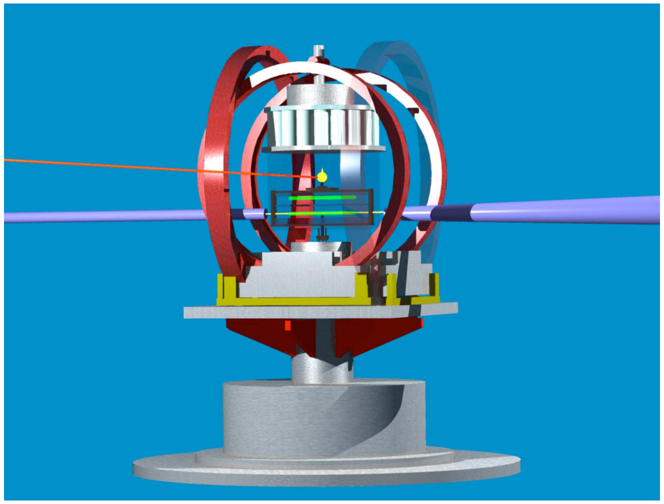
75-80% polarized beam at 15μA

35-40% polarized target in beam

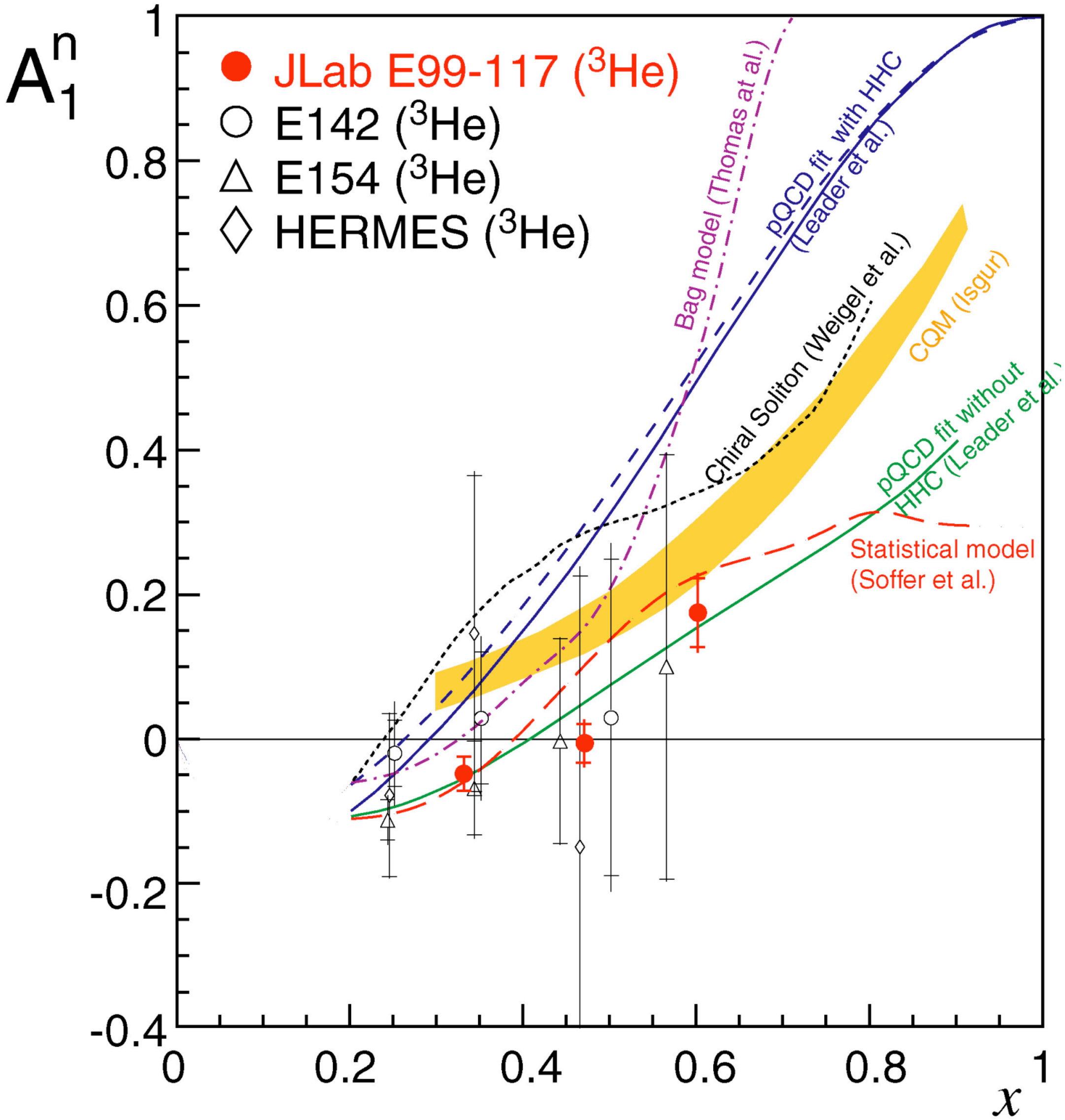


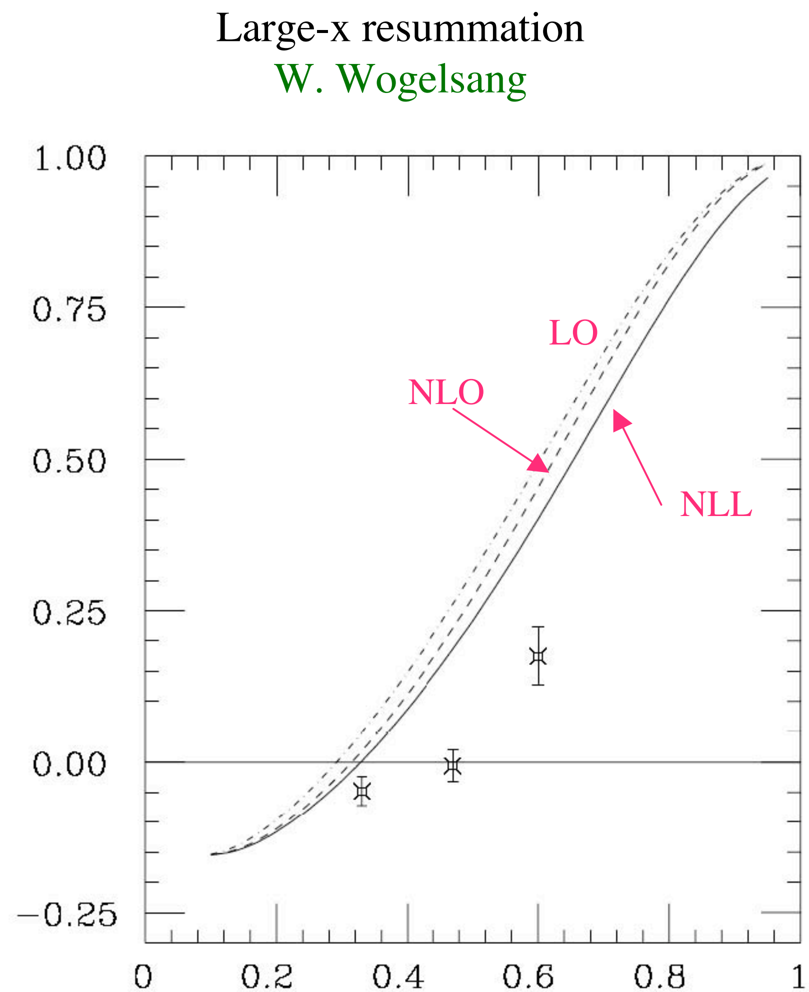


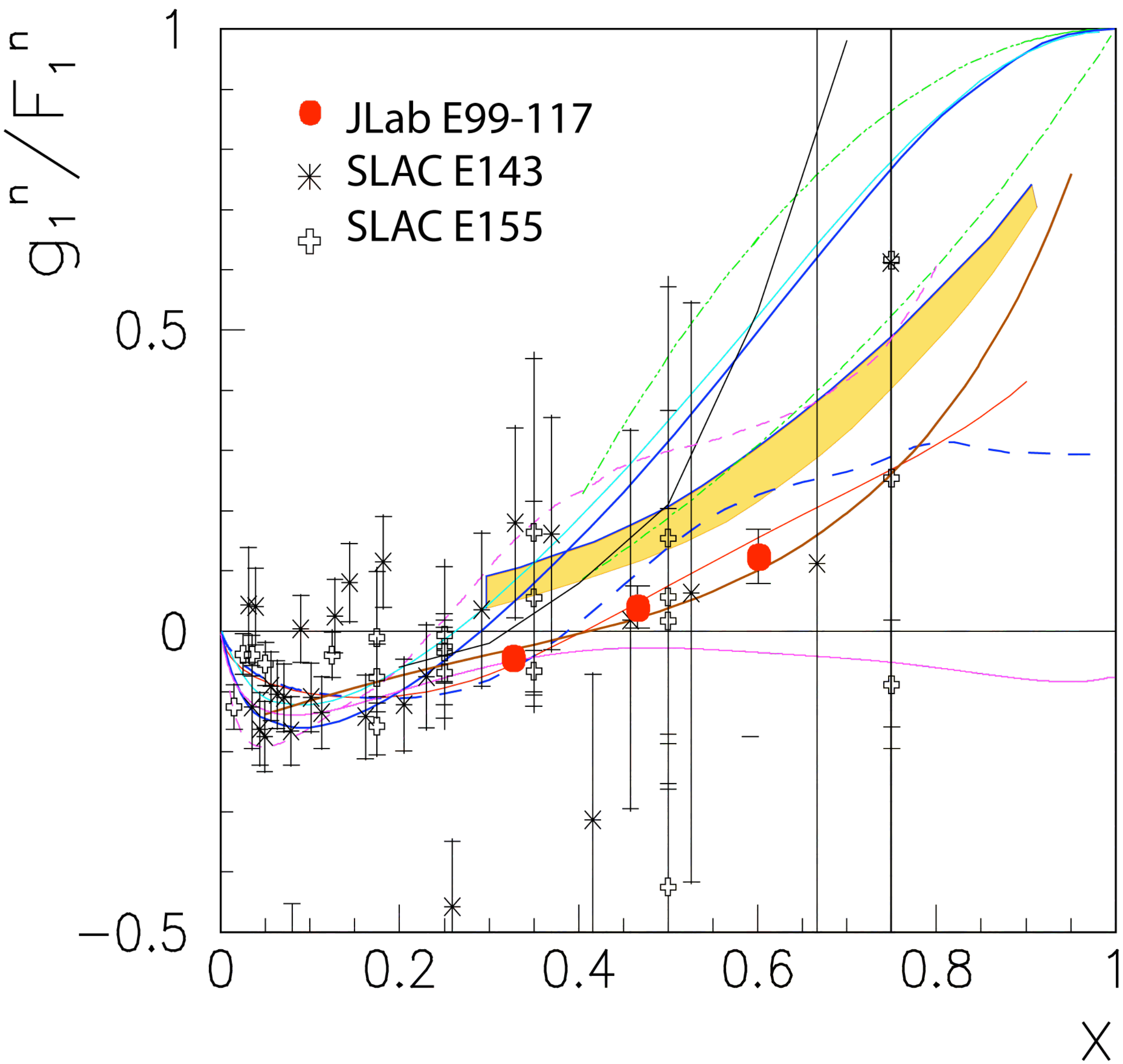
Polarized target



A_1^n in DIS from ^{3}He in Hall A







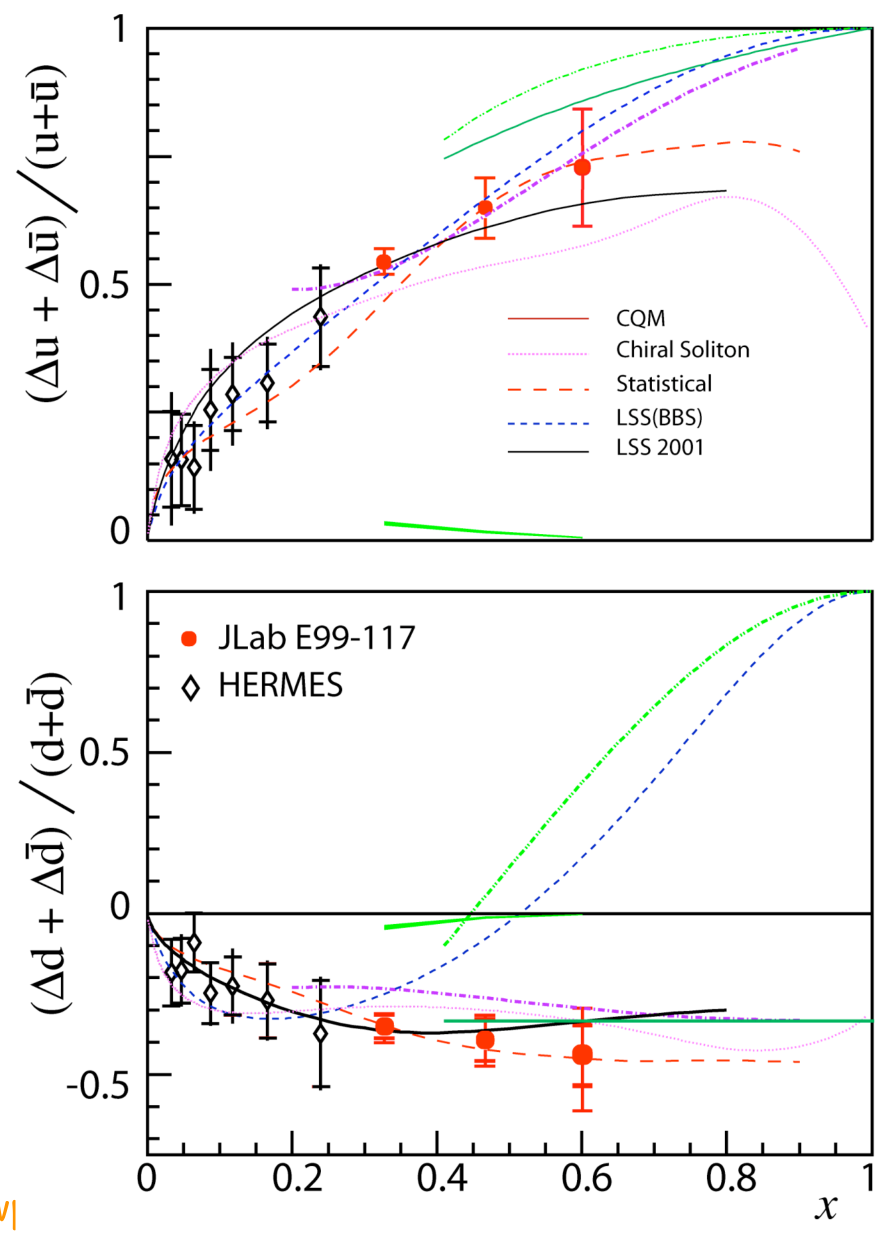
g_1^n/F_1^n
1
0.5
0
−0.5
0
0.2
0.4
0.6
0.8
1
X
JLab E99-117
SLAC E143
SLAC E155

Flavor Decomposition of PDFs

$$\frac{\Delta u + \Delta \overline{u}}{u} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4 + R^{du}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1 + 4R^{du})$$

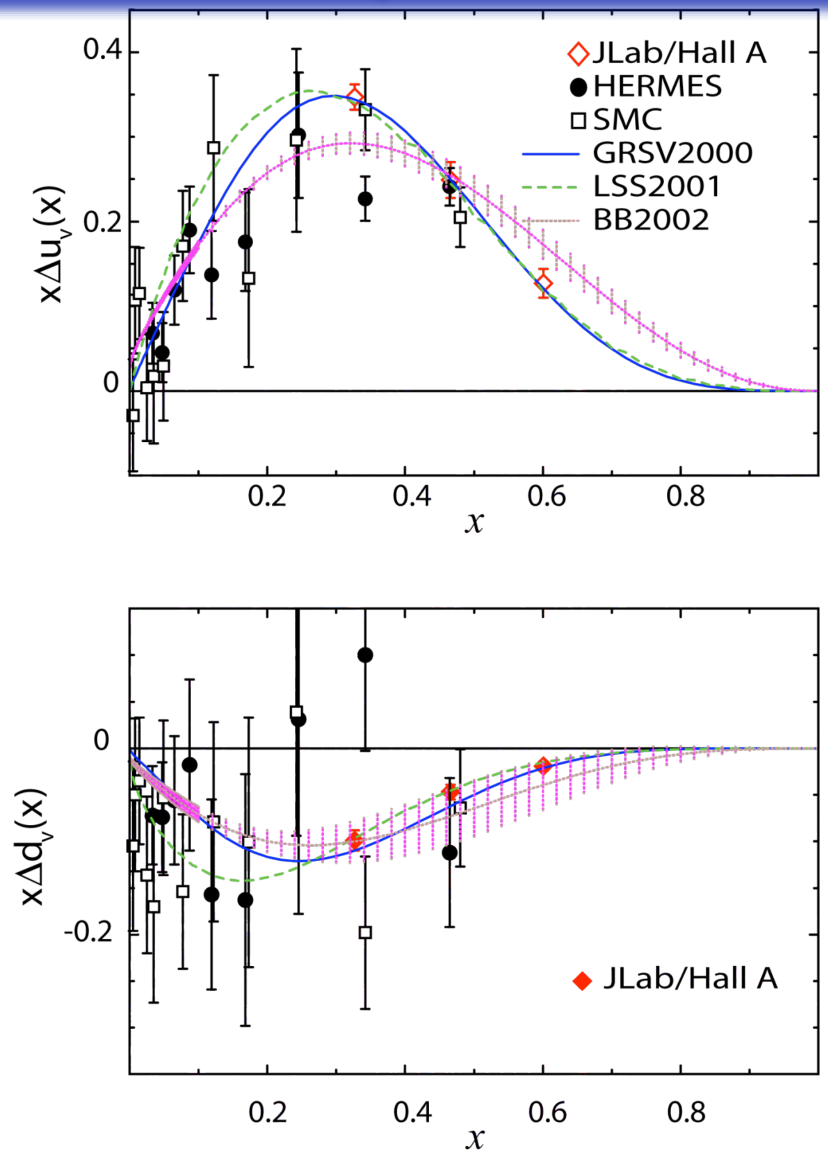
$$\frac{\Delta d + \Delta \overline{d}}{d} = \frac{4}{15}\frac{g_1^n}{F_1^n}(4 + \frac{1}{R^{du}}) - \frac{1}{15}\frac{g_1^p}{F_1^p}(1 + 4\frac{1}{R^{du}})$$

$$R^{du} = \frac{d + \overline{d}}{u + \overline{u}}$$

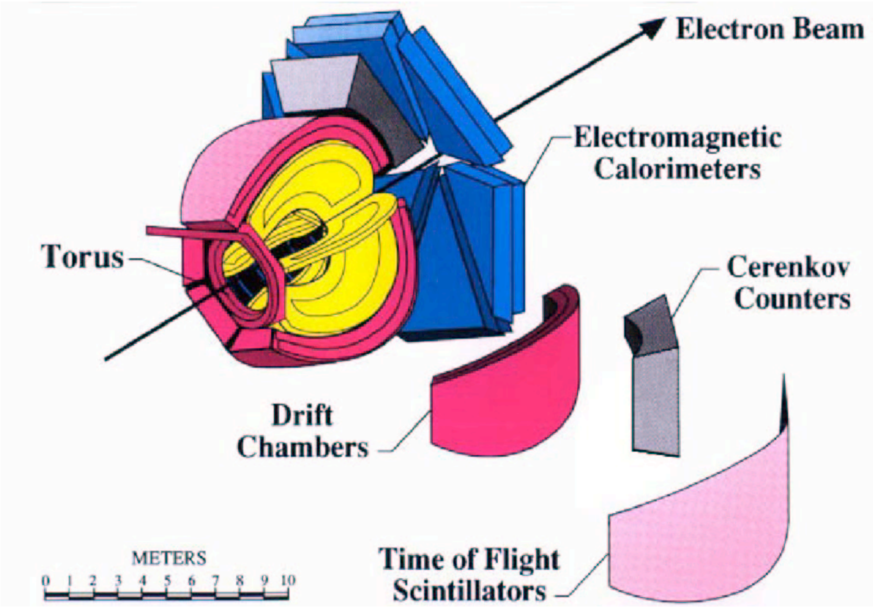


X. Zheng et al. **PRL** 92, 012004 (2004)
and **PRC**70, 065270 (2004)

Flavor Decomposition: PDFs

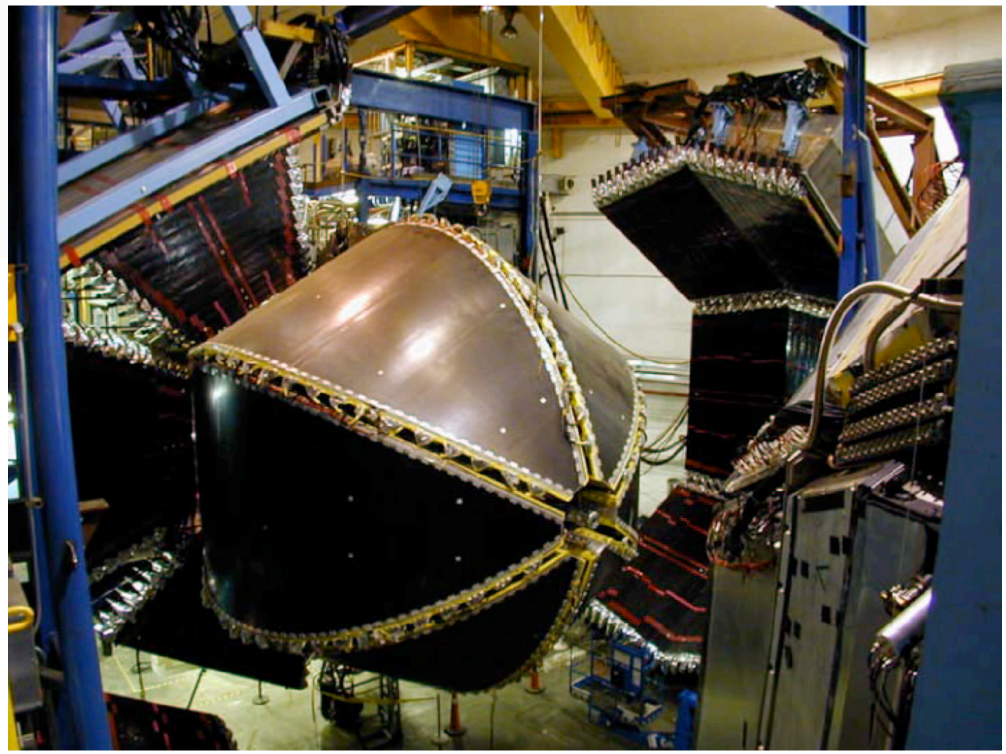


Hall B Experimental Setup



CEBAF
Large
Acceptance
Spectrometer

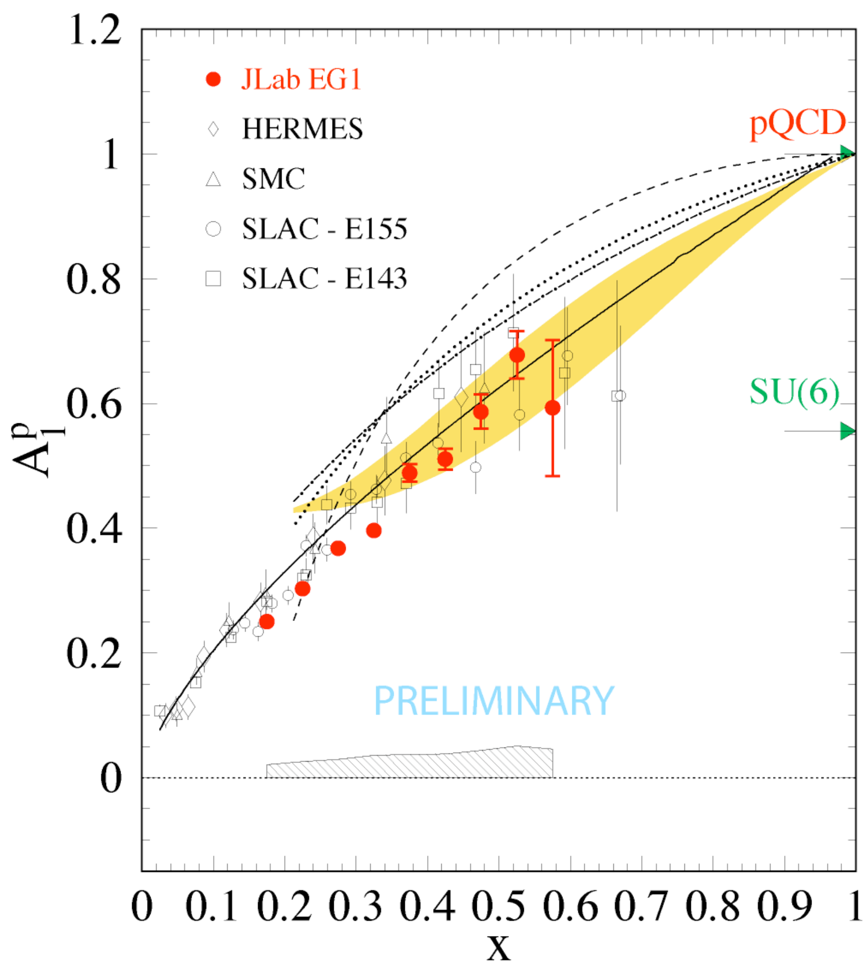
- NH3 and ND3 targets
- Beam current 100nA

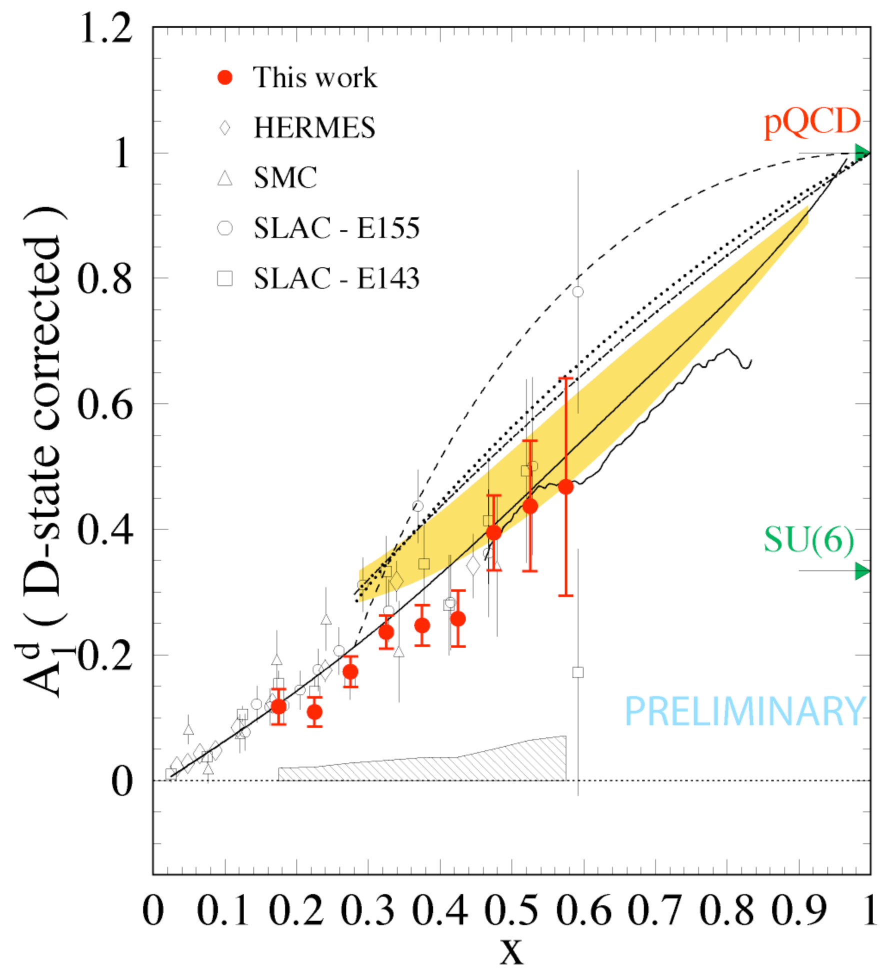


- Large kinematical coverage
- detection of charged and
  - neutral particles
- Multiparticle final state

$A_1^{p,d}$ From NH_3 and ND_3 in Hall B

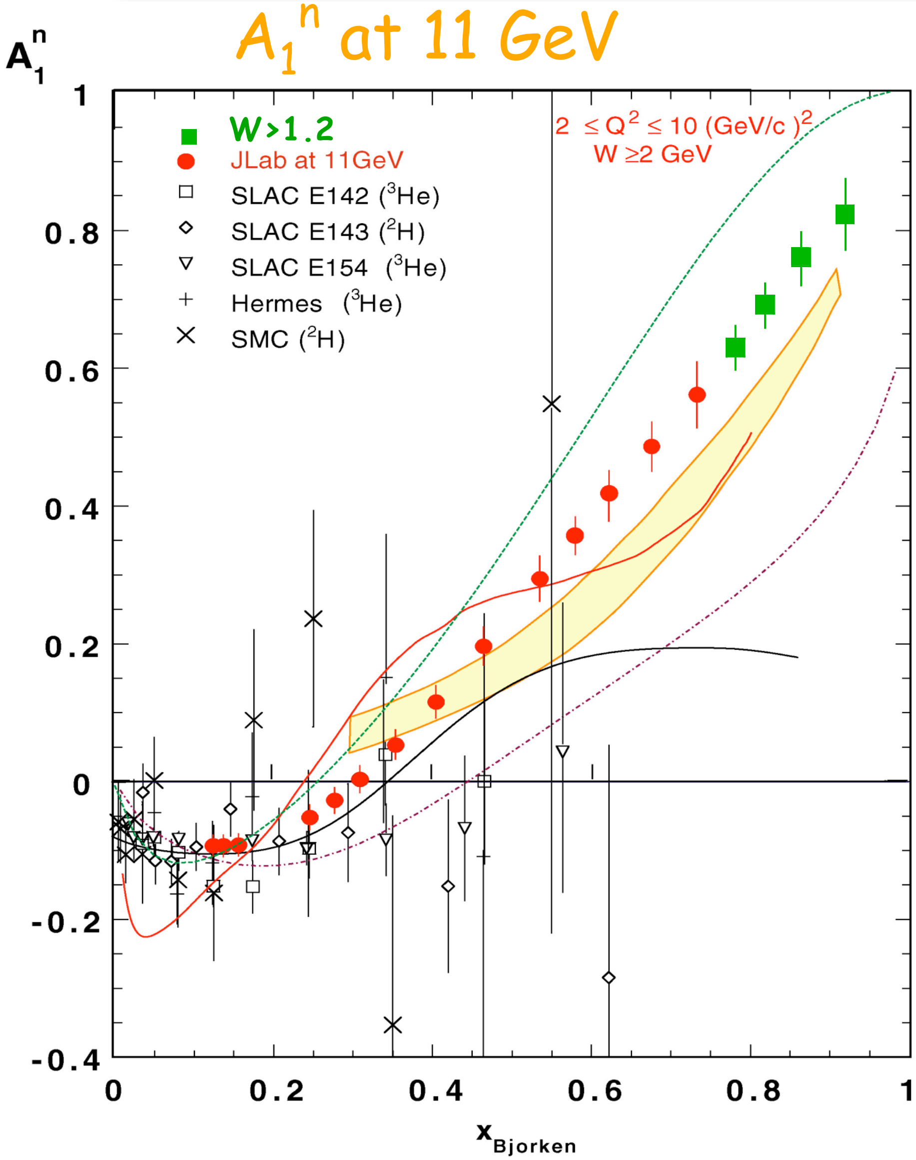
V. Burkert, S. Kuhn R. Mineheart, G. Dodge et al. EG1 collaboration





What's possible with 11 GeV beam

A_1^n at 11 GeV



A_1^p at 11 GeV